Invited Speakers

Understanding the impact of mobile ions on perovskite solar cells

Petra Cameron
University of Bath

The dual electronic-ionic nature of perovskite solar cells has greatly complicated their characterisation; impacting almost all of our 'standard' PV characterisation techniques. For example, when ions move on the timescale of current-voltage measurements, they can act to modify carrier recombination rates and carrier extraction, influencing the shape of the response. Ions can also modify fast measurements, where the ‘frozen in’ ion distribution impacts the electronic response of the device. The prevailing narrative in the literature is that the presence of these mobile ions is bad for perovskite solar cells, whether leading to field screening that lowers efficiency or contributing to material degradation. In this presentation I will consider whether ions are always bad for our devices, or whether they can also be beneficial. I will introduce our electrochemical measurements where we use ions as diagnostic probes inside perovskite solar cells. Finally, the talk will look at whether we can design cells differently to better take advantage of the intrinsic ionic properties of perovskite materials.

Solar Opportunities for Low-Carbon and Affordable Community Energy

Shahab Dehghan
Newcastle University

Solar power offers significant potential to reduce carbon emissions while lowering household energy costs. However, despite rapid technological progress, many communities, particularly social housing, face structural, financial, and regulatory barriers that limit access to rooftop solar and related low-carbon technologies. This presentation explores how community-scale solar integration can support an affordable and equitable transition to net zero. Building on the SUNRISE and SOLACE projects, it examines innovative approaches to rooftop solar integration/utilisation with different ownership models to extend the benefits of local renewable resources beyond individual homeowners. The talk will introduce a socio-techno-economic framework that coordinates building-level technologies, such as photovoltaics, batteries, and heat pumps, with local electricity network constraints. By unlocking the collective flexibility of neighbourhoods, these approaches can reduce peak demand, improve the financial viability of distributed renewables, and potentially defer costly grid upgrades. Beyond technical modelling, the presentation considers public adoption, fairness in energy sharing, and the role of local authorities and network operators in enabling scalable community energy solutions. The overall aim is to demonstrate how well-designed solar integration strategies can simultaneously accelerate decarbonisation, reduce energy bills, and address fuel poverty in urban neighbourhoods.

PV reliability at the tera-watt scale

Dr Nicholas Grant
University Of Warwick

Silicon photovoltaics (PV) will play a major role in establishing energy security for the UK and achieving Net Zero. To reach and sustain Net Zero beyond 2050, new PV installations must outpace replacement installations, both domestically and globally. However, as the number of replacement installations increases, there is growing concern that global PV production will become overwhelmed by the amount of manufacturing required to replace modules, thus placing substantial pressure on PV manufacturing at the tera-watt scale. This presentation will address the future challenges facing manufacturers, in particular the need to balance replacement manufacturing with stable growth in new PV production at the tera-watt scale. I will discuss the importance of doubling the lifespan of PV modules (e.g. ~50 years), whilst maintaining/increasing cell efficiency, and what this means for sustainable PV manufacturing at the tera-watt scale. By increasing module reliability, manufacturing quality will improve which in turn reduces pressure on PV production, reduces strain on raw materials and limits the amount of waste generated.

Space Photovoltaics for emerging applications

Louise Hirst
University of Cambridge

Rapid development in the space sector places new demands on the photovoltaic power system. Missions on an unprecedented scale such as Space based solar power, lunar bases and space data centres require MW arrays assembled on orbit for long duration delivery of services. Array cost and high production throughput system are critical for these applications, as well as extended mission lifetime in hostile environment with particle radiation bombardment and temperature extremes, as well as UV and atomic oxygen exposure. In addition, these applications require lightweight stowable form factors for low-cost launch and on-orbit array assembly. While III-V multijunction devices are the established platform for space applications evolving demands of the sector maybe served by other material systems or design adaptations.

This talk will outline emerging opportunities for PV development within the space sector and highlight our work on device adaptation targeting these requirements including routes to lower cost through alternative materials synthesis techniques and longevity on orbit with ultra-thin geometries.

Enhancing the stability of OPVs without compromising their sustainability

Julianna Panidi
University of Edinburgh

Organic semiconductors offer a promising route toward sustainable optoelectronics, yet their widespread commercialisation remains constrained by two critical challenges: the need for eco friendly, scalable processing methods and the requirement for long term operational stability. Although recent material innovations have enabled high efficiencies under both indoor and outdoor illumination, these performances are still typically achieved using petroleum based, toxic solvents that are incompatible with green manufacturing and large scale device production. At the same time, achieving stability under real world operating conditions is essential to translate laboratory breakthroughs into durable technologies.

In this talk, I will show how material selection plays a crucial role in determining overall device stability, with an emphasis on novel polymers featuring low synthetic complexity that yield high performing blends. The OPV systems presented here are processed using the biorenewable solvent 2 MeTHF. We demonstrate a power conversion efficiency (PCE) of 14.5% for a PTQ10:Y12 blend and 11.2% for FO6 T:Y12, combined with excellent operational stability, achieving T_{80} values exceeding 2280 hours. To elucidate the origins of this enhanced stability, we further investigate these systems using low temperature and light dependent measurements to probe their underlying photophysical and morphological behaviour.
Finally, to understand the influence of processing additives on long term OPV stability, we extend our analysis to additional material systems. Together, these results highlight the potential of green processing and rational material design to advance scalable, durable, and environmentally compatible organic photovoltaic technologies.

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Understanding heterogeneity in quasi-2D perovskite photovoltaics

Alex Ramadan
University of Sheffield

Quasi two-dimensional (2D) perovskites have garnered significant research attention due to their promising optoelectronic properties such as high emission quantum yields and absorption coefficients. Their structural diversity makes them suitable for an array of optoelectronic applications such as light emitting diodes, field effect transistors, and solar cells. The structure of quasi-2D perovskites feature layers of perovskite octahedra intercalated along the (001) direction by bulky organic spacer cations such as n-butylammonium. These cations increase the hydrophobicity and lattice rigidity of the material, which is suggested to result in an improved stability in the presence of moisture than their 3D counterparts.

Despite this stability benefit, the power conversion efficiency of quasi-2D perovskite PV lags behind their 3D counterparts. This has been ascribed to a reduction in out-of-plane carrier mobility caused by the quasi-2D perovskite sheets preferentially orienting parallel to the substrate, and the organic cation layer acting as a barrier to charge transport. To overcome this, considerable efforts have been undertaken to attempt to induce vertical growth of 2D sheets such that the perovskite layers form normal to the substrate. Ammonium thiocyanate (NH4SCN) has been used extensively to improve current extraction and power conversion efficiencies in quasi-two-dimensional (quasi-2D) Ruddlesden Popper perovskite solar cells. However, a detailed understanding of the mechanism through which it improves device performance has not been established, limiting its use to only a few perovskite compositions.

In this presentation I will discuss our work to understand the structural effect of ammonium thiocyanate (NH4SCN) in quasi-2D perovskites, focussing on the formation and distribution of 2D and 3D perovskite domains in thin films and resultant improvements in photovoltaic performance. Finally, I will show that the effect of NH4SCN differs with perovskite composition, in particular highlighting the pivotal role of the spacer cation on the choice of additive.

Measurement challenges of perovskite-silicon tandem cells

Martin Schubert
Fraunhofer Institute for Solar Energy Systems ISE

Perovskite–silicon tandem solar cells present distinct challenges for electrical and optoelectronic characterization. The monolithic integration of the sub-cells and the availability of only two electrical terminals complicate accurate measurements of quantum efficiency and current–voltage (I–V) characteristics, while the metastable nature of perovskite absorbers, particularly ion migration, introduces pronounced time-dependent effects. Establishing robust characterization protocols for such metastable multi-junction devices requires stringent control of the spectral conditions and carefully defined electrical and optical biasing schemes for external quantum efficiency (EQE) measurements and spectrally adapted I–V characterization.

In this presentation, we discuss advanced techniques for quantitative sub-cell analysis based on photoluminescence imaging and spectrometric methods, alongside industrially compatible high-throughput measurement approaches, and address the associated characterization challenges, supported by detailed simulation.

Updates from the Engineering & Physical Science Research Council

Adam Suttle
UKRI

This talk will provide an overview of the evolving funding landscape across UK Research and Innovation and Engineering and Physical Sciences Research Council, with a particular focus on how recent changes to the UKRI investment model shape the broader context for solar research and innovation.

As UKRI transitions to a new, outcome-focused funding framework aligned to government priorities, the talk will outline the four ‘bucket’ model for investment and the continued role of curiosity-driven, investigator-led research within this system.

Oral Presentations

Integrated Molecular, Interface, and Passivation Approaches to Ultra-Efficient Indoor and BIPV Perovskite Photovoltaics

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Abstract:

Perovskite photovoltaics continue to push the boundaries of efficiency and stability through synergistic materials and interface engineering. Here, we present a multimodal framework that unifies buried-interface modulation, molecular passivation, and band-structure control to achieve outstanding performance in both semi-transparent devices and wide-bandgap indoor photovoltaics. First, we demonstrate a multimodal strategy that integrates optimized optical design, transparent electrode engineering, and targeted molecular passivation to overcome the traditional transparency–efficiency trade-off in semi-transparent perovskite solar cells and modules. This approach yields state-of-the-art semi-transparent devices with competitive PCE and light utilization metrics, enabling scalable transparent photovoltaics for building-integrated applications. Second, we report buried-interface engineering via a multifunctional polymer matrix that homogenizes SnO_2 dispersion, eliminates interfacial defects, and achieves improved grain orientation. The resulting devices deliver enhanced power conversion efficiencies with negligible hysteresis and robust long-term operational stability, highlighting the critical role of interface quality in high-performance perovskite cells. Finally, we introduce a Triple Passivation Treatment (TPT) reassembly that simultaneously suppresses bulk and surface defects in wide-bandgap perovskites and induces an n- to p-type surface energetics modulation. This enables record 37.6% indoor power conversion efficiency under 1000 lux illumination, alongside excellent shelf and light-soaking stability. Together, these advances underscore how co-optimized molecular design, interface manipulation, and passivation architectures can unlock new performance frontiers for perovskite photovoltaics — from transparent/BIPV modules to ultra-efficient indoor energy harvesting, pointing toward scalable and durable deployment pathways.

Dr Mojtaba Abdi-Jalebi

Associate Professor in Functional Materials & Energy Devices

UCL
Institute for Materials Discovery

Bio: Dr. Mojtaba Abdi-Jalebi (FIMMM, FHEA, GYA) is an Associate Professor in Energy Materials at the Institute for Materials Discovery within the Faculty of Mathematical and Physical Sciences at University College London (UCL). He earned his BSc in Materials Science and Engineering from Sharif University of Technology in 2012 and completed his MSc in Materials Science and Engineering at École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland in 2014. In 2018, Dr. Abdi-Jalebi received his PhD in Physics from the Cavendish Laboratory at the University of Cambridge, where he was honored with the 2018 Semiconductor Physics Thesis Prize by the Institute of Physics. From 2018 to 2020, he served as a Junior Research Fellow at Cambridge University and Wolfson College, Cambridge. During this time, he established a spin-out company focused on developing energy harvesting devices based on emerging semiconductors. In November 2019, Mojtaba established his research group at UCL, concentrating on the material and electronic properties of emerging semiconductors such as halide perovskites, small molecules, and organic semiconductors. The group's research is dedicated to optoelectronic and electrochemical devices for low-cost electronics applications, including solar photovoltaics and lighting, as well as energy systems supporting carbon capture and the production of solar fuels. Dr. Abdi-Jalebi's overarching research goal is to introduce new, cost-effective materials into energy devices, ultimately reshaping the energy landscape. His work aims to contribute to the transition to a net-zero future by reducing the cost of green energy production, consumption, and storage. Mojtaba is Fellow of the Institute of Materials, Minerals and Mining (FIMMM), member of Global Young Academy (GYA) and Fellow of the Higher Education Academy (FHEA).

FMED
Functional Materials and
Energy Device group

Circular Economy in Printable Perovskite Solar Cells

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Critical materials such as graphite underpin the performance of emerging photovoltaic (PV) technologies but face increasing supply-chain pressures due to geographic concentration, geopolitical risk, and growing global demand. Embedding circular economy principles into PV manufacturing offers a pathway to reduce reliance on virgin critical materials while lowering environmental impact. At Newcastle University, we investigate circular economy strategies for printable triple-mesoscopic perovskite solar cells, focusing on both upstream (materials and design) and downstream (use and end-of-life) processes.

In the upstream processes, our focus has been on replacing conventional carbon electrode components with recovered alternatives. Graphite has been replaced with recovered graphite from manufacturing scrap and mixed spent batteries. Carbon black has been replaced with recovered carbon black from waste tyres [1], or biochar derived from waste biomass. These recovered-carbon formulations are compatible with scalable deposition methods and deliver comparable, or in some cases enhanced electrode functionality, demonstrating that materials from waste streams can be valorised.

Complementing this, downstream circularity is explored through thermal and vacuum-based performance recovery processes [2]. We show that post-degradation treatments remove water presence from within the perovskite grain boundaries responsible for performance loss but are effective only before irreversible structural degradation occurs. Our findings reveal that open-circuit voltage and short-circuit current density device parameters can serve as early indicators of reversible hydration-induced degradation. This enables preventive maintenance and contributes to closed-loop strategies for printable PV modules.

Together, this work highlights a dual circularity approach – sourcing recovered carbon materials upstream and enabling device performance recovery downstream – to support resilient supply chains, reduce critical-material dependency, and advance sustainable manufacturing routes for next-generation solar technologies.

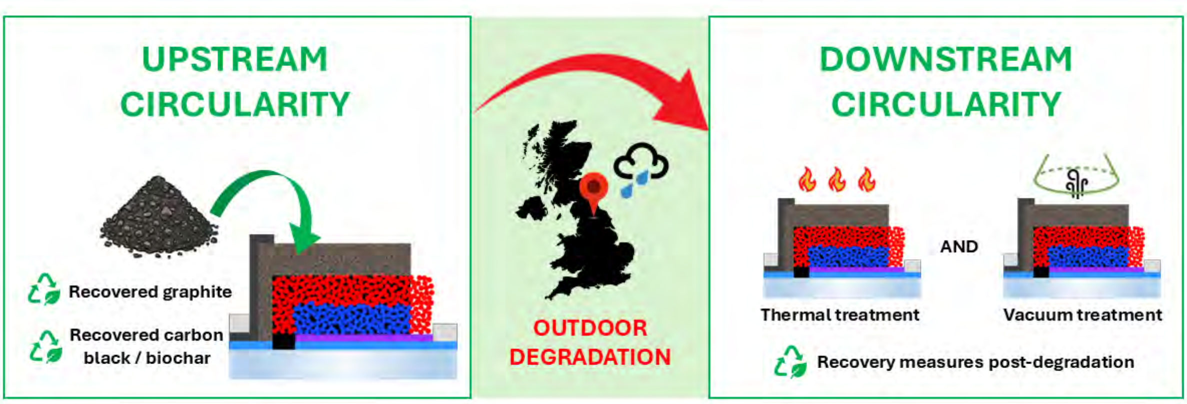

Figure 1. Upstream and downstream circular economy strategies for printable perovskite solar cells.

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5. Perovskite, organic, tandems and DSSC photovoltaics

Novel Carbon-Based Electrode Materials for High-Performance Emerging Solar Cell Technologies with Enhanced Sustainability

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Among the most promising emerging thin-film photovoltaic (PV) technologies, organic and perovskite solar cells (OSC and PSC, respectively) have attracted unprecedented attention from both academia and industry in recent decades. Starting with power conversion efficiencies (PCEs) of only a few percent, OSCs have now reached nearly 20% efficiency.[1] In comparison, PSCs have surpassed 26%.[2] Similar progress has been observed in the operational stability of both PV technologies. Most reported high-efficiency and stable devices, however, rely on evaporated opaque metal contacts, typically gold (Au) or silver (Ag).[3] Both metals present challenges: Au is expensive, and the price of Ag has recently risen sharply, adding cost pressures to existing stability concerns associated with large-scale deployment of Ag top electrodes in PSCs.

To address these challenges, we report the development of graphene-enriched carbon inks suitable for use as electrodes in PSCs and other optoelectronic applications. The inks (Figure 1a) were developed by GraphEnergyTech and validated in PSC architectures (Figure 1b) fabricated at the University of Surrey as part of an Industry Collaboration Program funded by the Henry Royce Institute. The graphene-based inks exhibit high electrical conductivity, are solution-processable, and can be cured in as little as 1 minute at 100 °C, allowing easy integration into industrial manufacturing processes. Ultimately, we demonstrate PSCs with carbon-based electrodes achieving high PCEs comparable to devices employing metal electrodes. This work supports the commercialisation of next-generation solar technologies and strengthens the UK's leadership in sustainable energy materials.

Figure 1 a) Graphene enriched carbon inks developed by GraphEnergyTech and b) Photograph of a PSCs with carbon-based electrodes.

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1. Conference Topic

Multi-Bridged Lewis-Functionalized Interfacial Engineering for Enhanced Crystallinity and Stability in Inverted Perovskite Photovoltaics

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Inverted (p-i-n) perovskite solar cells (PSCs) require robust interfacial layers to minimize non-radiative recombination and ensure long-term operational stability. Conventional hole-transporting self-assembled monolayers (SAMs) often suffer from limited surface coverage and weak anchoring, leading to interfacial degradation under stress. In this study, we introduce a strategic interfacial engineering approach utilizing a novel asymmetric SAM architecture designed with a multi-bridged phosphonic acid anchoring system [1].

This molecular design integrates multiple anchoring groups to establish thermodynamically stable bonding with the substrate, significantly enhancing durability compared to single-anchored counterparts. Furthermore, strategically positioned Lewis-basic heteroatoms within the molecular backbone induce synergistic interactions with the perovskite overlayer. These interactions effectively passivate under-coordinated surface defects and promote a "face-on" molecular orientation, which optimizes energy level alignment and facilitates efficient charge extraction [1].

Crucially, the modified interface serves as a template for superior perovskite crystallization. Building upon our previous studies on additive engineering [2] and stereochemical control of crystallographic orientation [3], we demonstrate that this multi-bridged SAM strategy significantly enlarges perovskite grain size and suppresses grain boundaries. Consequently, the resulting devices exhibit minimized dark current density and substantial improvements in fill factor and short-circuit current. The enhanced interfacial integrity also imparts superior resistance to moisture ingress, offering a promising pathway for designing highly efficient and stable perovskite optoelectronic devices.

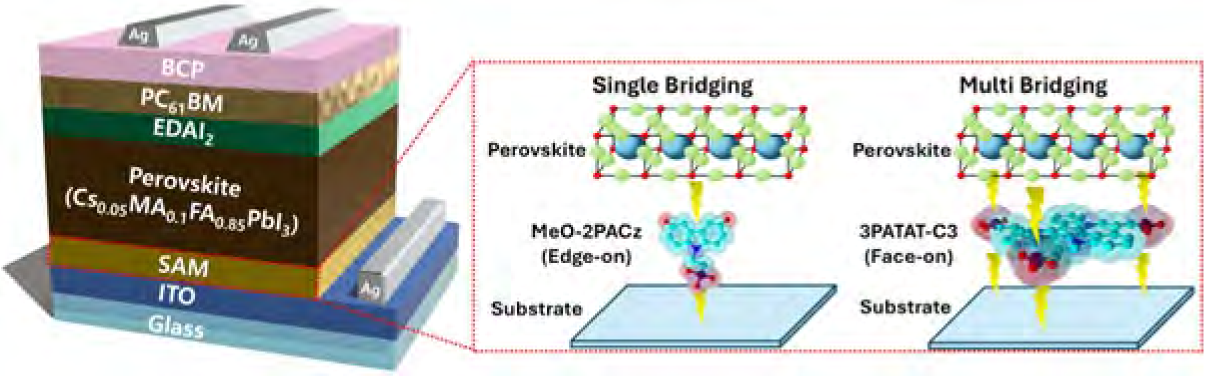

Figure 1 Multi-Bridged Lewis-Functionalized Self-Assembled Monolayers for Enhanced Interfacial Affinity in Perovskite Photoelectric Devices”

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ALD coatings for wettability control on anti-soiling PV glass

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The accumulation of dust and dirt on the surface of solar panels (soiling) causes a reduction in power output by 2–50% depending on location and frequency of cleaning [1, 2]. Traditional cleaning methods are resource-demanding, labour-intensive and potentially damaging to the solar module. Anti-soiling coatings (ASCs) offer a passive solution by reducing soiling from precipitation runoff and/or photocatalytic degradation of organic material deposited on the module's surface.

Atomic layer deposition (ALD) is an established, cost-effective method for conformal thin film (<100 nm) deposition with proven industrial scalability. This work explores the use of ALD to deposit ~20 nm metal oxides (e.g. Al_2O_3 and HfO_2) onto glass substrates, and establishes the role of ALD parameters, pretreatments and post-deposition modifications on the wettability of the coating. We characterise wettability through water contact angle (WCA) measurements and assess the film's composition and morphology using atomic force microscopy (AFM), X-ray photoelectron spectroscopy (XPS) and scanning electron microscopy (SEM). We explore multiple techniques to tune the contact angle, including: (1) corona charging to deposit surface charge, which can switch Al_2O_3 films from hydrophilic (0–10°) to more hydrophobic (60–90°), (2) hot DI-water (DIW) immersion to develop a "grass-like" morphology, that influences the wetting behaviour and chemical composition of the surface, and (3) different ALD growth methods (plasma-enhanced and thermal) to change the film's composition [3, 4]. Temporal stability and chemical composition are characterised using repeated WCA measurements and XPS, respectively, to evaluate observed changes in wettability.

By connecting surface characterisation with wetting behaviour, we aim to develop guidelines for ALD-based ASCs for solar glass which allows for a critical step towards durable and scalable real-world applications.

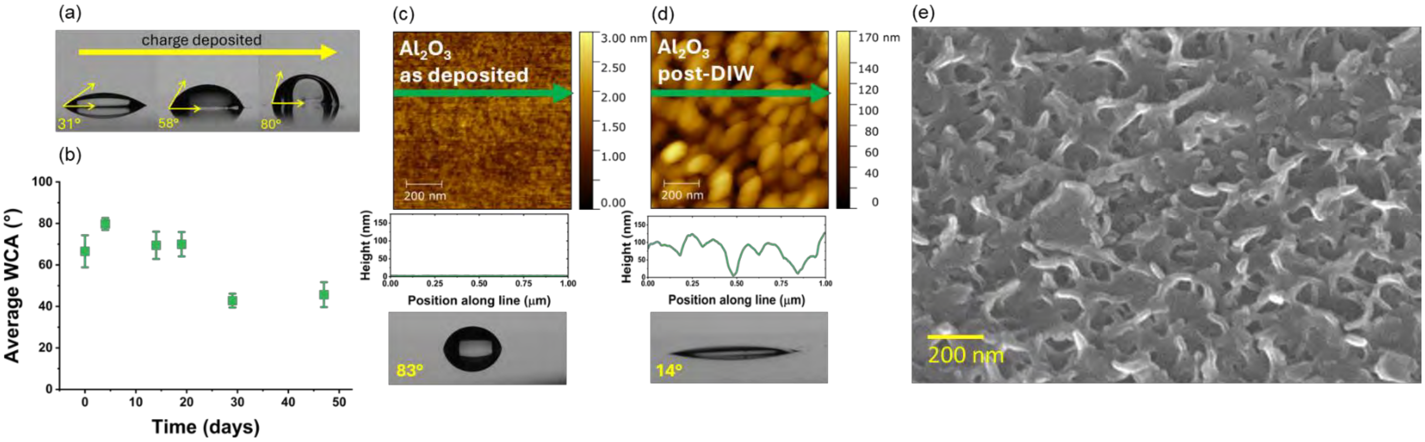

Figure 1: (a) effect of charge deposited on water contact angle (WCA), (b) stability of charged Al_2O_3 surface over time, (c, d) AFM of Al_2O_3 before and after DIW-treatment, with water droplets below to show wettability changes, (e) SEM of "grass-like" alumina on glass.

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The Impact of Transparent Conducting Electrodes on Tandem Solar Cell Efficiency

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Perovskite–silicon tandem solar cells are a leading approach for pushing photovoltaic efficiencies beyond the ~29% limit of single-junction silicon [1]. Monolithic two-terminal (2T) tandems have already reached certified efficiencies above 34% [2], with laboratory targets of 37–38%. This progress comes from combining wide-bandgap perovskite top cells, which provide high voltage and tuneable absorption, with mature crystalline silicon bottom cells. Accurate modelling is essential to understand the real efficiency limits of these tandems. Recent models include realistic recombination, absorption, and optical coupling and predict a practical efficiency limit of about 38% for 2T perovskite–silicon devices [3]. Similar studies in silicon cells show that contacts, band alignment, and optical design are key to approaching material limits [4]. However, most models neglect an important loss mechanism: transparent conductive electrodes (TCEs). While optical absorption in TCE layers is often included, lateral resistive losses and their dependence on grid geometry are usually ignored. In practice, TCE sheet resistance, finger spacing, and metal shading create unavoidable trade-offs that directly limit power output.

In this work, I present a combined optical–electrical model that quantifies efficiency losses caused by realistic TCEs in monolithic 2T tandems (Fig 1a). Closed-form expressions are used to describe lateral resistive losses, which are integrated into a multi-diode circuit model solved with PySpice (Fig 1b). Optical losses are calculated using the transfer matrix method for common TCE stacks, including antireflection coatings and buffer layers. The model identifies optimal finger spacing and evaluates the maximum achievable efficiency as a function of TCE conductivity and transparency. While perovskite–silicon tandems are used as a benchmark, the approach applies to any tandem combination. The results show that TCEs are a major efficiency limiter. Even a single typical TCE (e.g. 50 nm ITO with an antireflection coating) reduces tandem efficiency by more than 2% absolute, lowering a 37% ideal device to about 35.1% (Fig 1c). Additional TCEs, often required in real tandems, further increase losses. These findings are consistent with experiments showing that small changes in TCE deposition or optical stacks lead to measurable efficiency gains.

The design implications are clear. TCEs must be optimized together with antireflection layers and transport barriers as a single optical stack. Grid design must be treated as a key parameter, balancing resistive and shading losses for each TCE material. Finally, as recombination and interface losses approach their limits, TCEs will become the main factor determining whether tandems can move from today's ~34% toward the 37–38% efficiency target. In summary, this work shows that TCEs are not auxiliary layers but core performance-limiting elements in tandem solar cells. The proposed model provides practical guidance for optimizing materials, optics, and grid design to enable the next generation of high-efficiency tandem photovoltaics.

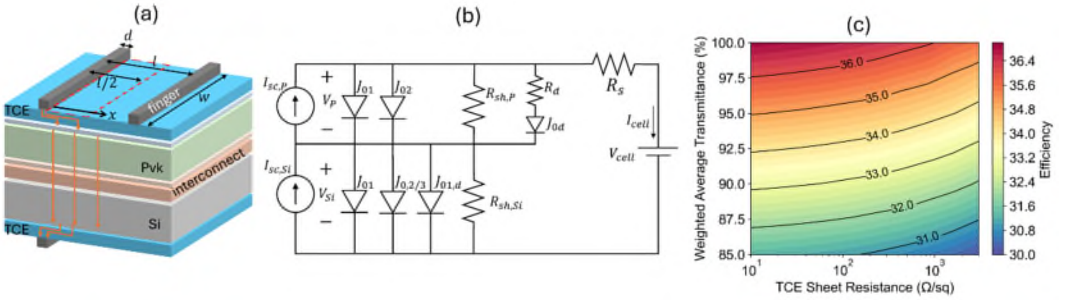

Figure 1 (a) Unit domain of a two-terminal tandem solar cell, (b) Multi-diode model, (c) tandem efficiency as a function of TCE WAT and R_{sh}

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Geometric Stabilization and Alkyl-Chain Engineering Enable High-Performance Cu-Based HTMs for Solid-State DSSCs

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Copper complexes have recently emerged as promising hole-transport materials (HTMs) for solid-state dye-sensitized solar cells (DSSCs). However, their performance is often limited by the substantial geometric reorganization accompanying the Cu(I)/Cu(II) redox transition, where oxidation-induced ligand flattening slows interfacial hole transfer and promotes recombination. To mitigate these distortions, we designed a bipyridine ligand (C1C4) bearing flexible n-butyl substituents at the 6,6′-positions to resist oxidation-induced planarization. The resulting Cu(I) and Cu(II) complexes, $[Cu(I)(C1C4)_2]BF_4$ and $[Cu(II)(C1C4)_2]BF_4$, adopt highly similar, near-orthogonal coordination geometries with short Cu–N interactions, as confirmed by single-crystal X-ray diffraction and supported by DFT calculations. These structural features collectively contribute to a substantially reduced internal reorganization energy.

In contrast to conventional solid-state assembly, our devices employ a rapid solid state configuration, a faster and simpler fabrication method that places strict demands on the film-forming properties of the HTM.[1] Traditional copper-based HTMs typically exhibit surface defects under these conditions, leading to inefficient charge extraction and enhanced recombination. In CuC1C4, the incorporation of longer n-alkyl substituents improves intermolecular interactions and suppresses excessive crystallization, enabling the formation of uniform, low-defect thin films that meet the requirements of this architecture. This superior morphology facilitates efficient interfacial charge transfer, as reflected by the enhanced solid-state photoluminescence and the strong quenching (>97%). Electrochemical and UPS measurements further confirm that its HOMO level is well aligned for dye regeneration, while impedance spectroscopy reveals extended recombination lifetimes.

Device testing under both simulated sunlight and indoor lighting further demonstrates the effectiveness of this HTM. Under 1-sun, CuC1C4 delivers power conversion efficiencies of approximately 10%, accompanied by open-circuit voltages approaching 1.0 V. Under indoor white-LED illumination, the devices achieve efficiencies exceeding 36% (1000 lux), positioning CuC1C4 among the best-performing copper-based HTMs for low-light photovoltaic applications.[2]

Overall, this work demonstrates that targeted ligand engineering is an effective strategy for advancing copper-based HTMs in solid-state and low-light DSSCs. By simultaneously minimizing the geometric reorganization accompanying the Cu(I)/Cu(II) redox couple and enhancing film-forming properties through flexible 6,6′-alkyl substitution, CuC1C4 achieves improved interfacial charge transfer, reduced recombination losses, and outstanding device performance across diverse illumination conditions. These results highlight the potential of geometrically stabilised, solution-processable copper complexes as competitive HTMs for next-generation indoor and quasi-solid-state photovoltaic technologies.

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Improved optoelectronic homogeneity of perovskite photovoltaics through bottom-up design

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Self-assembled monolayers (SAMs) have emerged as a promising approach for the development of high-efficiency perovskite single-junction and tandem solar cells. Among the SAMs developed, (4-(3,6-dimethyl-9*H*-carbazol-9-yl)butyl)phosphonic acid (Me-4PACz) has enabled some of the highest efficiencies reported to date [1,2]. In this work, we employ both poly[(9,9-bis(3′-((N,N-dimethyl)-N-ethylammonium)-propyl)-2,7-fluorene)-alt-2,7-(9,9-dioctylfluorene)]dibromide (PFN-Br) and alumina nanoparticles (Al_2O_3 NPs) as surface modifiers to address a key limitation of Me-4PACz—namely, the poor wettability of perovskite precursors on the Me-4PACz surface, which leads to low device yields [3-5].

Although both surface modifications lead to improved device yield, Al_2O_3 NP based-modification results in significantly longer photoluminescence decay lifetimes, exceeding 3 µs, compared to PFN-Br-based modification. This translates to power conversion efficiencies exceeding 20% for perovskite solar cells (PSCs) fabricated on Me-4PACz modified with Al_2O_3, outperforming devices based on PFN-Br-modified Me-4PACz. We show that this approach has broader applicability across different SAMs including Ph-4PACz, I-2PACz and mixed SAMs. Beyond improvement in device performance, Al_2O_3-based surface modification also significantly improves device stability under ISOS-D-2I and ISOS-D-2 testing conditions (65 °C). In particular, Al_2O_3-modified PSCs exhibit a T_{80} lifetime of 1530 h under ISOS-D-2 conditions, a tenfold increase compared to PFN-Br-modified devices. Scanning Kelvin probe force microscopy and scanning conductivity mapping of both as-prepared and degraded films reveal higher inhomogeneity in surface electronic and bulk electrical properties for PFN-Br-modified samples, which further increases upon degradation. In comparison, Al_2O_3-based modification yields improved homogeneity in both fresh and aged samples, indicating that enhanced bottom-up homogeneity is a key factor driving device stability.

This work uncovers the importance of careful tuning of the buried interface towards improving both efficiency and stability of perovskite photovoltaics.

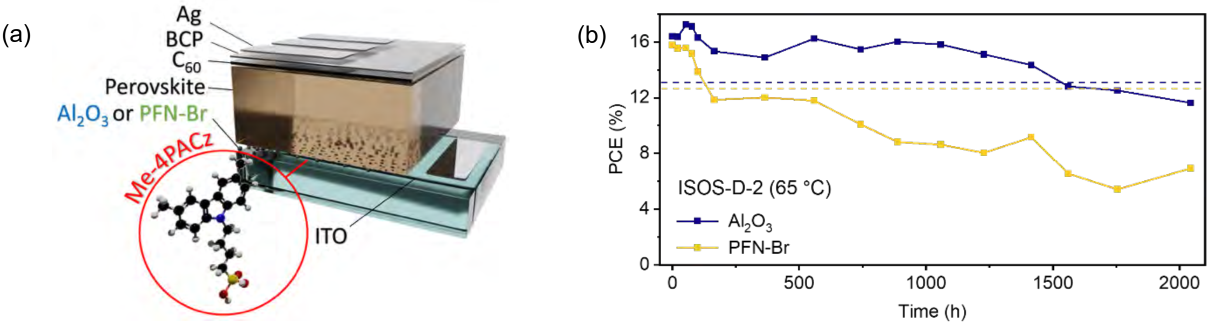

Figure 1 a) Device architecture of the perovskite solar cells. b) Stability testing of champion devices based on PFN-Br and Al_2O_3 NPs under ISOS-D-2 conditions.

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4. Perovskite, organic, perovskite-based multijunction and DSSC photovoltaics

Ethanol-based Green Solvent System for Fabricating Perovskite Solar Cells

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Perovskite solar cells (PSCs) have achieved significant attention in recent years due to their high power-conversion efficiencies (PCE) and potential for low-cost fabrication. With rapid development, the PCE of the PSCs have reached up to 27% [1]. A solution-processable method to make PSCs is the most standardized method, using various solvents and anti-solvents to promote the rapid crystallization of perovskite, which will result in high-efficiency PSCs [2]. Environmental-friendly methods are very important for the commercialization of the PSCs[3]. However, the solvent-processing method for making devices can lead to environmental issues because most solvents used are toxic [2-5]. Normally in the perovskite precursor, the DMF/DMSO system is used, but DMF is a toxic solvent. Additionally, many typical anti-solvents such as chloroform, diethyl ether, toluene and so on are also toxic [2]. To fabricate large-area PSCs in factories, it is important to choose green solvents to protect people's health and a sustainable environment.

In this work, we developed an ethanol-based green solvent system to replace conventional toxic solvents such as DMF. Although the common perovskite absorber material $FAPbI_3$ is poorly soluble in ethanol, we achieved successful dissolution by introducing a Lewis base additive and the bulky RNH_3Cl (where R is a large organic group) that both coordinate with lead ions[2]. By optimising the ratios of such additives, as well as spin-coating and annealing parameters, we obtained phase-pure α-$FAPbI_3$ perovskite films with high crystallinity. Through this approach, we achieved perovskite solar cells with promising initial efficiency.

Figure 1. a) 4-(Trifluoromethyl)benzamidine hydrochloride; b) 1-(2-Aminoethyl)maleimide hydrochloride

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1. Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

Mechanical and Compositional Characterisation of PV Module Laminates to Inform High-Value Recycling Pathways

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The global deployment of crystalline silicon photovoltaic (PV) panels has grown exponentially over recent decades [1], but end-of-life (EOL) recycling and materials recovery remain significant challenges. With these panels having an industry standard lifespan of 25-30 years, recyclers face a substantial influx of PV waste. Current UK recycling infrastructure is not equipped to manage the projected volumes or retain critical raw materials within domestic supply chains, with UK solar waste expected to exceed current pan-European recycling capacity by 2035 [2].

A key barrier to scaling PV recycling is the limited characterisation of module construction and, in particular, the adhesive properties of encapsulants that bond the panel. Ethylene-vinyl acetate (EVA) remains the industry-standard encapsulant due to its optical performance, low cost, and resistance to environmental degradation. However, variations in EVA layer thickness, formulation, and lamination conditions across manufacturers significantly influence the mechanical strength of the adhesive and therefore the forces required to separate PV components during recycling.

This study investigates the adhesion behaviour of EVA-glass interfaces representative of those in silicon PV modules. Pull-off adhesion tests were conducted to quantify bonding strength, failure modes, and failure locations, providing critical baseline data for the design of debonding processes in future recycling technologies. Complementary materials characterisation was performed on multiple EOL panels using SEM and EDX on waterjet-cut cross-sections to determine layer thicknesses, identify thin-film coatings, and map compositional variability across manufacturers.

Combining adhesion testing with detailed structural and compositional analyses enables identification of the most valuable material layers and the separation strategies that require the lowest mechanical energy input. This integrated approach provides an evidence base for optimising future PV recycling processes, improving raw-material recovery, and supporting sustainable management of the rapidly growing EOL PV stream.

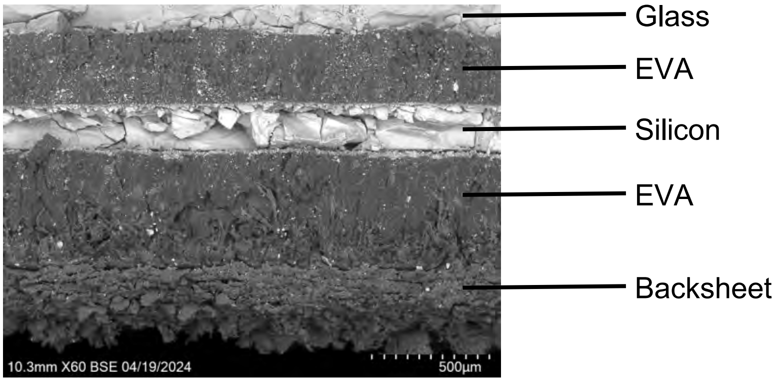

Figure 1 a) SEM image of waterjet-cut PV panel cross-section with individual layers labelled.

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1. PVSAT 2026

Grain-Boundary Passivation and Band-Gap Engineering in CZTSSe via a Low-Temperature $CdCl_2$ Process

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Abstract: $Cu_2ZnSn(S,Se)_4$ (CZTSSe) is a promising earth-abundant absorber for thin-film photovoltaics, yet its efficiency remains limited by a persistent Voc deficit. This work introduces a simple and scalable $CdCl_2$ treatment that significantly improves device performance and can be applied at different stages of fabrication to achieve either alloying or doping. When $CdCl_2$ is deposited before selenization, cadmium incorporates into the CZTSSe lattice, forming a $Cu_2Zn_{1-x}Cd_xSn(S,Se)_4$ alloy that reduces the band gap and enhances long-wavelength absorption. In contrast, $CdCl_2$ applied after selenization results in cadmium accumulation at grain boundaries, passivating recombination sites and increasing both Voc and Jsc.

Characterization through SEM/EDXS, XRD, Raman, and SIMS confirms the distinct incorporation mechanisms and associated structural changes. Capacitance-voltage and DLCP measurements show an order-of-magnitude increase in carrier concentration for both treatments, with fewer compensating defects in the post-selenization case. Devices treated after selenization achieve efficiencies up to 8.5%, representing more than a 50% improvement over untreated references. Accelerated stability testing (80 °C, 1 sun) shows minimal degradation, demonstrating the robustness of the approach. This low-temperature, solution-based $CdCl_2$ process offers a versatile route for band-gap tuning or doping in CZTSSe absorbers, enabling significant performance enhancement with minimal process complexity.

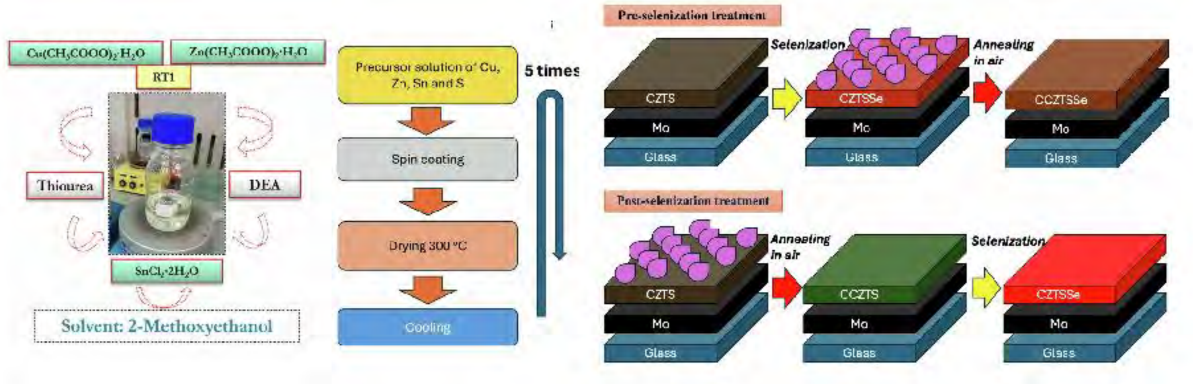

Figure 1: Process flow showing film deposition and the two $CdCl_2$ treatment procedures.

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1. Photovoltaic systems, solar irradiance and monitoring, policy, sustainability, market development and life cycle analysis

Exploring a simplified approach towards modelling of bifacial PV systems

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The Photovoltaic Geographical Information System (PVGIS), developed at the Joint Research Centre of the European Commission, is a free online tool developed to predict photovoltaic (PV) energy yield and provide irradiance data worldwide. In its current version, it can provide on the fly results for yield modelling of PV monofacial systems. Recently, bifacial PV technology has become increasingly common with around ~50% of all PV modules in the field now being bifacial.

In this work, we explored the addition of bifacial yield modelling capability to PVGIS. The energy yield for bifacial PV systems can be predicted using a back-to-back approach, by running the simulation twice – once for the front and once for the rear. This approach could overestimate the rear side irradiance since it does not consider shading from the modules. A robust 2D model to calculate rear side irradiance has been used. Rear-side irradiance models vary in approach and complexity. With fast computation times being a priority, a simplified infinite sheds model [1] was chosen to test robustness and accuracy of calculations. This approach was adapted by using Muneer's model for diffuse irradiance in place of the Perez model, to fit in with the current irradiance model used in PVGIS. This model was then implemented with the PVGIS power and temperature model formulae [2] and compared against experimental data from strings of PV modules installed outdoors, from the JRC's European Solar Test Installation (ESTI) site in Ispra. These results are also benchmarked against other commonly used open-access models. Different approaches to calculating module temperature are also compared and validated against experimental results.

This simplified approach to modelling bifacial systems produces results comparable with other open-source models and is found to be robust when tested for different orientations and tilt angles. Validating and benchmarking this model is an essential step in considering its implementation into a software package. Based on these results and implementation, the modified Vogt model [1] will be implemented into the next version of PVGIS (version 6).

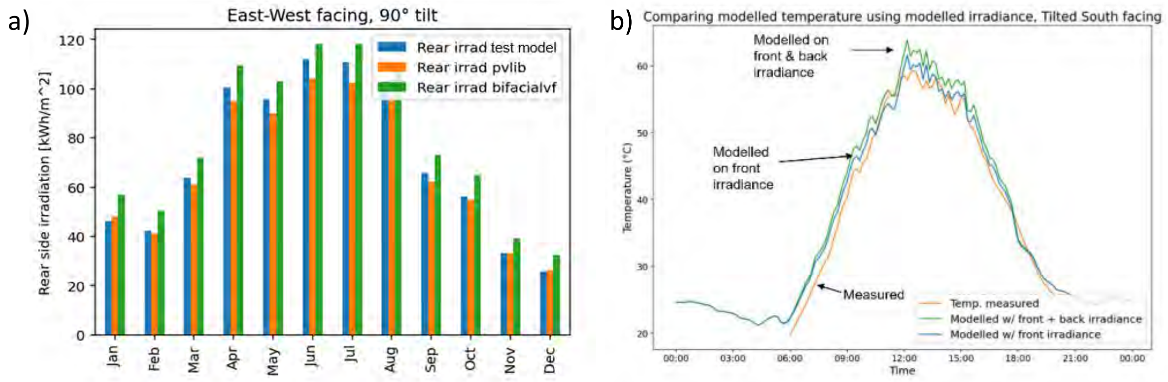

Figure 1a) A comparison of the test model against other common open-source bifacial PV models, b) comparison of using front irradiance or front and back irradiance to calculate module temperature using the Faiman module temperature model.

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Conference Topic: Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

Carrier Lifetime in Silicon Solar Cell Materials for Space Applications Using Temperature-Dependent Photoexcited Muon Spin Spectroscopy

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Silicon solar cells are widely used in space applications due to their cost-effectiveness and radiation tolerance. However, their performance at extreme temperatures, such as those encountered in low-earth orbit, require further study. In this study, we present novel temperature-dependent carrier lifetime measurements in industrially relevant silicon heterojunction (SHJ) solar cell and its base substrate, after removing the metal contacts, over the range 77 – 290 K using photoexcited muon spin spectroscopy (photo-μSR) at ISIS Neutron and Muon Source [1]. Photo-μSR is a pump-probe technique that allows depth-resolved carrier lifetime measurements in silicon wafers and fully processed solar cells. It involves generation of excess charge carriers by laser excitation followed by implantation of spin-polarised positive muons into a sample as shown in **Figure 1** (a). Interaction between muons and excess carriers induces muon spin relaxation and is directly related to the excess carrier density, enabling lifetime measurements in semiconductors such as silicon [2, 3]. Photo-μSR also enables separation of bulk and surface recombination in silicon, unlike conventional lifetime techniques (e.g., photoconductance decay) with the additional benefit of photo-μSR's applicability to completed solar cells.

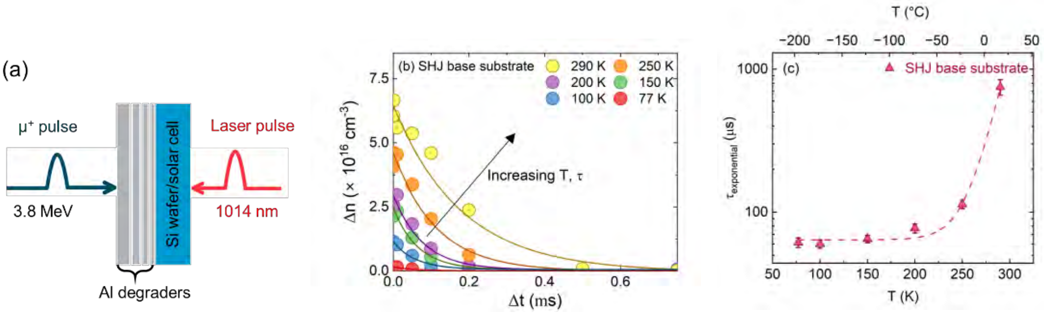

Figure 1. (a) Schematic of muon implantation and laser excitation. (b) Excess carrier density (Δn) as a function of time delay between the laser and the muon pulse (Δt) at distinct temperatures for SHJ base substrate. (c) Temperature dependence of carrier lifetime for SHJ base wafer measured from 77 – 290 K.

Figure 1 (b) shows the variation in excess carrier density (Δn) with the time delay between the laser and the muon pulse (Δt) for SHJ base substrate at varying temperatures, demonstrating that the decay in excess carrier density becomes slower as temperature approaches 290 K. Our results show a strong temperature dependence of carrier lifetime in both the silicon substrate and the completed SHJ device. In each case, lifetime increases nearly exponentially with temperature as shown in **Figure 1** (c) for the substrate. Similar trends were obtained for the SHJ solar cell with metallization with lifetime values lower than that obtained for the substrate. This behavior may be attributed to suppressed carrier freeze-out effects due to low concentration of free carriers at low temperatures. These early findings are essential for understanding the performance and reliability of silicon solar cells in extreme space environments and highlight the strength of photo-μSR in studying space PV technologies.

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Sustainable PV Manufacturing with Micro-Groove Architecture

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Perovskite solar cells (PSCs) have emerged as a leading candidate for next-generation photovoltaics due to their exceptional optoelectronic properties, high defect tolerance and low materials processing costs, especially when processed roll-to-roll (R2R). However, the field remains dominated by planar architectures that rely on indium-based transparent conductive oxides, which present cost, manufacturing complexity, and a serious long-term supply-chain risks [1]. Power Roll introduces a fundamentally different photovoltaic platform based on a unique embossed micro-groove architecture. Each groove's opposing sidewall is selectively coated with charge-transport layers, enabling R2R scalable buried-contact cells with built-in interconnection [2].

Unique advantages include inherent bifacial energy capture, high tolerance to localised defects and shading, and a streamlined manufacturing process with fewer patterning steps – key advantages over conventional planar PSCs. Importantly, the embedded contacts use Earth-abundant metals (e.g. nickel, titanium) instead of scarce materials such as indium, further lowering material costs and environmental impact.

Power Roll has scaled this concept from individual micron-scale groove cells into micro-modules consisting of hundreds of grooves [3]. These have been grown into >100 cm² mini modules via continuous R2R processing, and now into 600 mm x 400 mm flexible modules deployed in outdoor field testing, validating mechanical robustness, environmental durability, and real-world power output. This breakthrough platform paves the way to sustainable commercialisation of perovskite PV films for lightweight, adaptable solar applications - from building-integrated to vehicle-integrated photovoltaics, and off-grid systems [4].

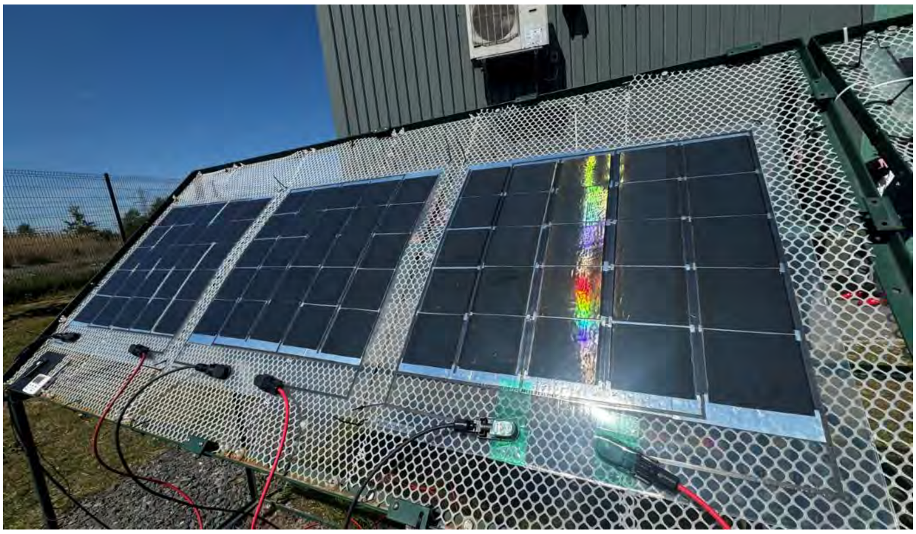

Figure 1. Photo of Power Roll's flexible modules.

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6.Photovoltaic systems, solar irradiance and monitoring, policy, sustainability, market development and life cycle analysis

Deep Analysis from Solar Assets to Define Circular Economy Pathways

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As utility-scale solar assets reach their midway lifespan (10-15 years), *repowering* is becoming a viable option for asset owners, facilitated by the supply of ever-decreasing costs of new and more efficient solar panels. Repowering provides solar asset owners with greater generation yield from the same landmass, but consequently places an abundance of reused solar panels on the secondary market, which are often exported to developing countries. However, there remains a challenge to provide cost-effective and comprehensive methods of differentiating between legitimate, working panels still of value via reuse pathways, and defunct panels which should be discarded as waste via established recycling pathways.

This study expands on previous research[1] by analyzing historical half-hourly (HH) data from a solar asset, providing a comprehensive 'health check' report based on the overall performance of the site and requisite components (e.g., inverter, combiner box, string). Using the case study of a 10-year-old 8 MW solar site and coupled with local environmental data[2] and site operations and maintenance (O&M) logs, global and local generation patterns are cross-correlated with *1.16 billion* HH timestamps to identify anomalous strings and establish a risk factor for the acquisition of the asset down to component level, including failure prediction.

This process provides deeper analytical insights previously unavailable by existing methods, such as drone thermography, and overcomes the over-generalizations of performance ratio (PR), which do not account for the numerous micro-environmental changes or O&M servicing. Combined with an AI based lookup-system, wave state analysis, and novel "fault fingerprinting", this method identifies characteristics such as soiling, panel cleaning[3], and downtime. Component failures are identified in relation to weather events, such as precipitation and outages. Collectively, this approach provides telemetry that evaluates the assets performance from the overall system down to individual strings. This in turn keeps solar in operation for longer, adhering to the "prevent" aspect of the waste hierarchy.

This approach provides third party validation between the buyer and seller of the asset and has wider applications for O&M teams and asset managers to understand the asset they are responsible for. Remediation efforts can focus on components most likely to have the greatest improvement in generation at the lowest cost, contributing to more efficient solar production.

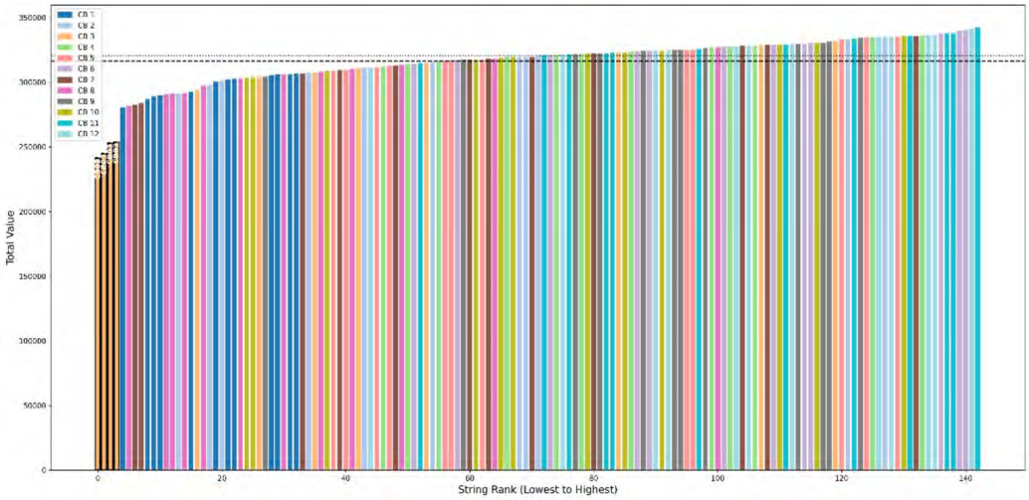

Figure 1) exemplar of 144 string ranking (inverter 1 of 5) based on algorithmic analysis

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1. Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

Coupled optical & electrical frequency domain spectroscopy to characterize defects in $Cu(In,Ga)Se_2$ solar cells

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A key factor limiting the performance of solar cell devices is the presence and nature of defect states in the absorbing semiconductor material. As such, electrical defect spectroscopy techniques such as admittance spectroscopy (AS) have been widely used to probe defect states close to the Fermi level in thin-film semiconductor devices like $Cu(In,Ga)Se_2$ (CIGS) solar cells [1]. The defects present close to the Fermi energy in doped materials like the p-type CIGS absorber layer are more sensitive to majority carriers. However, solar cell performance is more heavily linked to minority carrier dynamics; therefore, investigating traps that affect minority carriers could provide deeper insight into performance losses in thin-film solar cells.

An optical method of defect characterisation is modulated photoluminescence (MPL). MPL has previously been used as a method of determining carrier lifetime in Si wafers, and more recently for investigations into ion dynamics in perovskite materials [2]. MPL works in a similar manner to AS, using modulated laser excitation to fill and empty trap states at varying frequencies, allowing for the escape rate of the trap to be extracted. These escape rates can then be used to extract the capture cross section (σ) and activation energy (E_a) of the defect state [3].

In this work, we perform both MPL and AS on several CIGS solar cells and demonstrate that both characterization techniques independently probe different defect states in distinct regions of the band gap. This work serves as both an experimental proof of principle of temperature-dependent defect characterisation via MPL and as a direct comparison between novel (MPL) and well-established (AS) methods of defect spectroscopy.

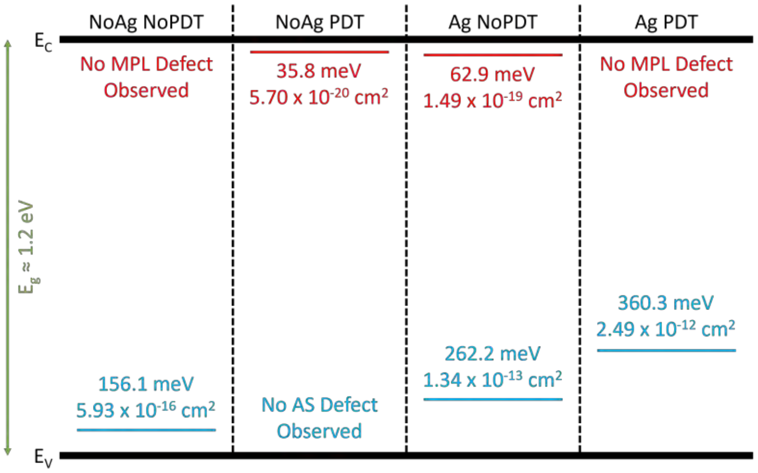

Figure 1: Schematic of the band structure of CIGS solar cells with defects probed by MPL (red) and AS (blue) depicted. Activation energies (respective to the nearest carrier band) and capture cross-sections are shown.

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1. Conference Topic

Advanced Anti Reflective Coatings for Space Solar PV

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Anti-reflection (AR) coatings are critical to minimising optical losses in high-efficiency photovoltaic (PV) devices. Multilayer dielectric stacks, such as a quarter wave bilayer, offer a route to broadband suppression of surface reflectance and consequently improved photocurrent generation. Molecular Vapour Deposition (MVD) provides precise, low-temperature thin-film growth and is particularly suited to AR coating fabrication due to its molecular-scale thickness control, high uniformity, and compatibility with temperature-sensitive substrates. In addition, MVD enables the deposition of diverse dielectric materials within a single process, supporting the development of multilayer stacks with tailored refractive-index contrast.

In this work, GaInP/GaAs multijunction solar cells incorporating TiO_2/Al_2O_3 bilayers were modelled using the Solcore optoelectronic simulation framework to determine the optimal layer thicknesses for space applications under AM0 conditions. Following optimisation, TiO_2/Al_2O_3 multilayers were deposited via MVD onto glass and GaAs substrates for experimental validation. The resulting layers were characterised using spectroscopic ellipsometry and UV-visible spectrophotometry to assess their refractive-index profiles and reflectance behaviour.

The optimised MVD-deposited layers reduced the reflectance of the GaAs substrate by approximately 28% at 850 nm, confirming the effectiveness of the simulated design. When integrated into the device model, this reduction in optical losses translates to improved light absorption in the active layers and consequently enhanced charge generation and power-conversion efficiency in the multijunction cell.

These results demonstrate that MVD is a highly promising manufacturing route for advanced AR coatings in III–V space photovoltaics, offering both precision and material versatility for next-generation high-efficiency space PV technologies.

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Topic 1. Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

Are you using an appropriate PV reference cell to measure your OPV device?

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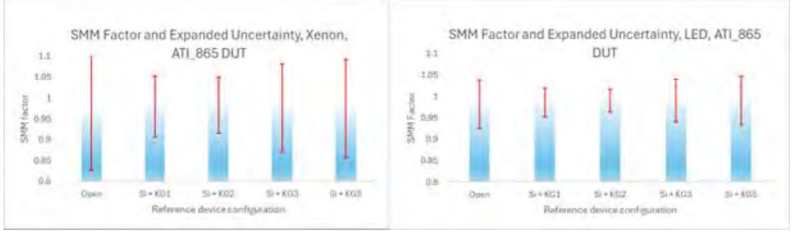
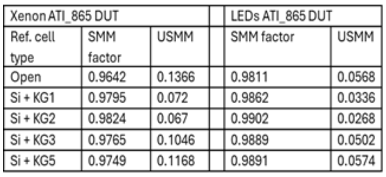
Non-fullerene acceptor (NFA) organic PVs have broken OPV power conversion efficiency (PCE) records, reaching around 21% [1]. Photoconversion typically extends into near infrared (NIR) wavelengths, by contrast to prior OPV technologies, generally limited to the visible [2]. This difference has significant implications for accurate performance measurements.

A solar simulator's artificial spectrum inevitably deviates from the AM 1.5G reference spectrum. This is especially important when the spectral response of the reference cell and device under test (DUT) differ. Accurate I-V curve and PCE measurement require a spectral mismatch (SMM) correction. The reference cell should match the spectral response of the DUT as closely as possible, especially when SMM corrections are not applied. Errors of up to 10% are possible if SMM is not calculated and a closely matched reference cell is not used.

This study calculated SMM factors for the widely used open silicon and KG5 reference cells, together with combinations including silicon and other optical filters in the same range as KG5, to identify the combination that minimises mismatch. NFA OPVs from the University of Surrey and EQE data from devices reported in the literature were assessed for SMM with both the Xenon and LED solar simulators at NPL. The silicon + KG2 combination showed lowest mismatch as can be seen in **Figure 1.**

The findings have significant impact on testing and reporting of NFA OPV devices, as using the correct reference cell for standard testing conditions (STC) measurements can mitigate deviations of up to 5% as in the example below, while 10% deviations have been observed for other samples. Resolving these issues can reveal the real potential of new technologies and help in accurate reporting of results in the literature. This also acts as an example of the importance of accurate measurements in PV development.





Xenon ATI_865 DUT				LEDs ATI_865 DUT	
Ref. cell type	SMM factor	USMM		SMM factor	USMM
Open	0.9642	0.1366		0.9811	0.0568
Si + KG1	0.9795	0.072		0.9862	0.0336
Si + KG2	0.9824	0.067		0.9902	0.0268
Si + KG3	0.9765	0.1046		0.9889	0.0502
Si + KG5	0.9749	0.1168		0.9891	0.0574

Figure 1 SMM with expanded uncertainty (95% coverage) for open silicon reference cell alone and with KG1, KG2, KG3 and KG5 optical filters for Xenon and LED solar simulators.The silicon + KG2 filter combination delivers the lowest mismatch factors and uncertainties. Example ATI_865 NFA OPV device supplied by the University of Surrey.

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AZO-based transparent conductive electrode for ITO-free OPV application

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Indium Tin Oxide (ITO) is widely used as Transparent Conductive Electrode (TCE) in Organic Photovoltaic (OPV) applications due to compatible chemical, electrical and optical properties. Unfortunately, Indium is rare and expensive increasing the cost of OPVs and making them unfeasible for large scale application [1, 2]. In recent years, Aluminium-doped Zinc Oxide (AZO) has been widely investigated as an alternative, due to its good conductivity and widespread availability. AZO possesses good optical transparency and electrical conductivity along with UV reflectivity, making it a good option for ITO-free OPV application [3, 4]. In this work, sputtered AZO is used as a TCE for OPV application. The sputtering process for AZO is optimized to produce AZO films with sheet resistance of 89 Ω/sq. and an AVT of 93%. OPV devices using AZO films are fabricated with the best cell having a Power Conversion Efficiency (PCE) of 7.6%. Further work is required to outperform ITO in terms of PCE, but AZO shows potential to produce cheap, ITO-free and stable devices.

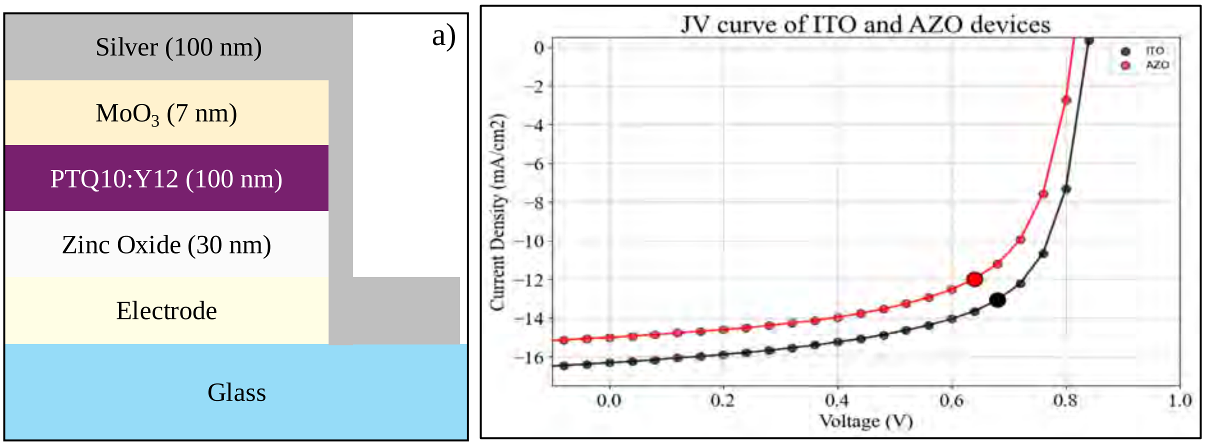

Figure. 1. a) OPV device architecture. b) JV curve of the best performing ITO and AZO devices with Maximum Power Point annotated.

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Conference topic: Inorganic thin film, inorganic multijunction and concentrator photovoltaics

Development of Ultra-Thin InGaP/GaAs Tandem Cells for Space Applications

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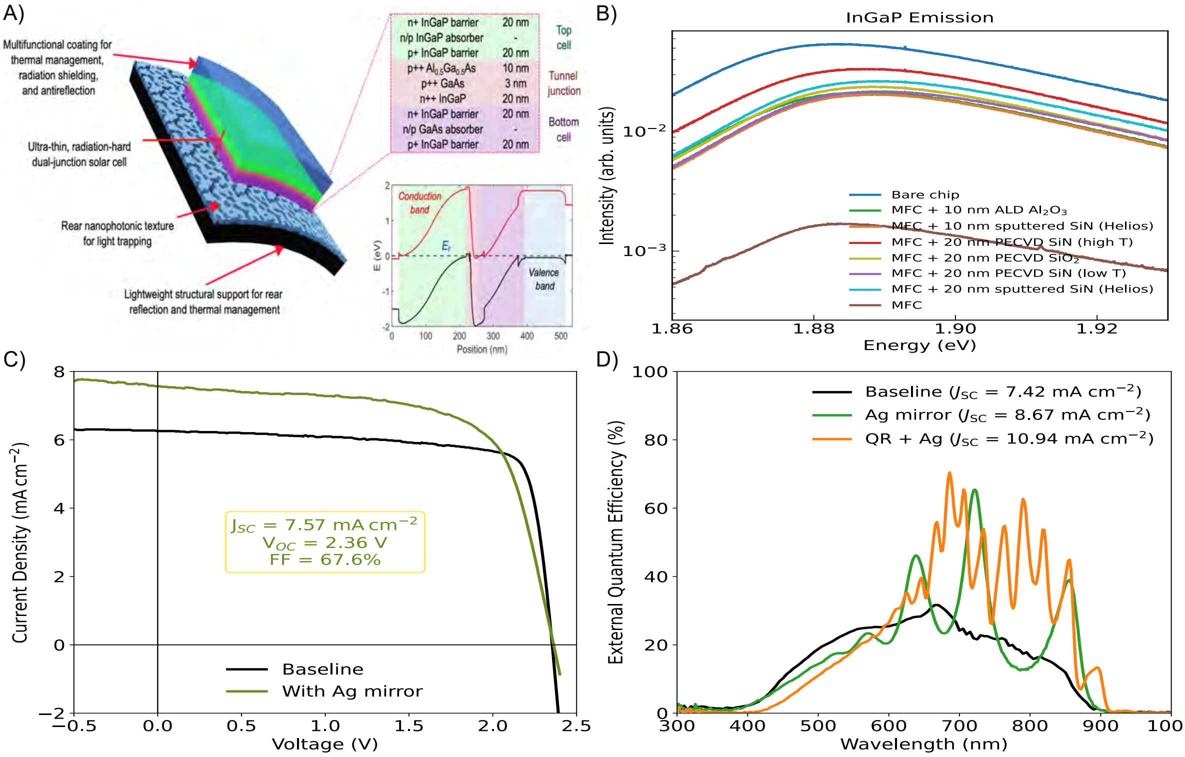
We present an ultra-thin InGaP/GaAs tandem PV concept (100–200 nm absorbers) for space applications. Ultra-thin architectures enable intrinsic radiation tolerance, flexible form factors, reduced material usage, and increased fabrication throughput. Advanced light management (ARC, rear Ag reflectors, and quasi-random/QR textures) targets AM0 J_{SC} of 15–18 mA cm^{-2}, comparable to tandems with 10× thicker absorbers. A 2 µm multifunctional front coating (MFC) replaces conventional coverglass, providing mass reduction, radiation shielding, antireflection, and radiative cooling (Fig. A).

A baseline device without ARC or light trapping achieves an AM0 η of 8.62%, with J_{SC} = 6.26 mA/cm^2, V_{OC} = 2.35V and *FF* = 79.1%. Adding a rear Ag mirror increases J_{SC} by 21% and η to 8.93% (Fig. C). Performance is currently limited by *FF*, which will be addressed via contact layout optimisation. The importance of light trapping in ultra-thin devices is demonstrated by EQE measurements. As absorption enhancement primarily occurs at longer wavelengths, Fig. D focuses on the GaAs bottom cell, where the QR scattering structure yields a 47% increase in integrated AM0 J_{SC}. Finally, we are developing a fully sputtered MFC for scalable and cost-effective integration. The primary challenge is surface damage during deposition. Protective interlayers were evaluated via InGaP PL measurements (Fig. B), confirming that a 20 nm sputtered SiN layer effectively suppresses sputtering damage. Successful MFC implementation is expected to substantially reduce front reflection and enhance radiation hardness, to be validated through particle irradiation testing.



A) Representative device schematic showing the layer stack and band structure. B) PL measurements of InGaP top cell with MFC + different protective interlayers, to assess material damage and protection effectiveness. C) Light I–V characteristics demonstrating performance improvement after incorporation of a rear Ag mirror. D) EQE measurements of the GaAs bottom cell highlighting absorption enhancement from different light-trapping strategies, integrated AM0 J_{SC} is used as the figure of merit.

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6. Photovoltaic systems, solar irradiance and monitoring, policy, sustainability, market development and life cycle analysis

Assessing the Environmental Impacts of Repowering UK Solar Farms

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Re-powering solar farms with upgraded photovoltaic (PV) technology is an important and emerging area of interest that is under-explored globally. This is particularly relevant given the silicon PV market's recent transition from passivating emitter rear cell (PERC) to tunnel oxide passivating contact (TOPCon) technology. The premise that this results in a larger generation of clean, green power is warranted as a result of higher efficiency achieved with TOPCon, but requires analysis to understand the environmental impacts of choosing to repower.

The study considers a 25-year temporal scope due to the warranty lifetime of PERC, performing life cycle assessments (LCAs) of three cradle-to-grave scenarios: (1) operating PERC in a solar farm for 25 years *("Baseline");* (2) operating PERC for either 10 or 15 years and replacing with TOPCon for the remaining period *("Repowering")*; and (3) operating with PERC for either 10 or 15 years, replacing with TOPCon for the remaining period and re-using the retired PERC modules on household rooftops *("Repowering and Reuse")*. Such re-powering times were chosen due to a UK solar report finding that industry efforts are active to re-power at 15 years or less [1]. Each scenario is divided into two different end-of-life treatments: landfill and recycling. A novel temporal impact assessment to the LCA results is derived and applied, demonstrating that *Repowering and Reuse* results in the lowest environmental impact across sixteen different categories. The study also finds a ~5% reduction in Greenhouse Gas (GHG) emissions from landfill to recycling for each scenario.

A statistical approach is used to estimate PV waste streams associated with repowering UK solar farms according to the scenarios outlined above. The UK Solar Roadmap [2] is used as a reference to calculate this waste stream to 2050, using a target of operational solar capacity of 90 GW. It is found that with appropriate re-powering, PV waste streams are reduced by ~5% per annum by 2050 without compromising UK solar capacity targets.

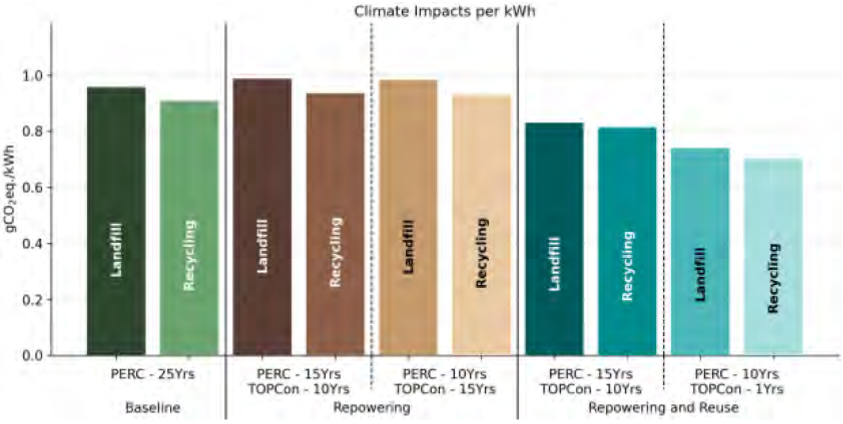

Figure 1 GHG impacts normalised to total energy output per module in each scenario.

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Transparent Conducting Electrodes for Perovskite-Silicon Tandem Solar Cells

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Transparent conducting electrodes (TCEs) are a critical bottleneck in TW-scale perovskite-silicon tandem cell manufacturing. Existing tandems depend almost exclusively on indium-based TCEs such as zinc-doped and tin-doped indium oxide (IZO, ITO), which contribute >2%abs PCE loss per layer used [1], and limit manufacturing capacity to <0.2 TW/yr. In this work, we critically evaluate the TCE-related optical, electrical and interfacial loss mechanisms in tandems, and establish a position-specific framework to understand and mitigate them. We reveal why conventional two-parameter TCE "figures of merit" fail for tandems, and identify key target TCE properties to mitigate losses in J_{sc}, FF and stability.

Fig. 1a depicts the requirements for TCEs in tandems. We explore position-specific requirements for TCEs at the front, mid and rear, investigating the competing constraints that govern interfacial band alignment, optical coupling, shunting, plasmonics, and low-damage deposition. Using examples from recent state-of-the-art literature, we outline practical design rules and evaluate the effectiveness of strategies including tailored crystallinity, multilayer and graded-index TCOs, buffer designs, and approaches based on 2D materials and hybrid nanocomposites. This provides a clearer basis for rational TCE design that will aid materials scientists and engineers to produce materials best aligned to device needs.

Finally, we present a roadmap for low-In and indium-free TCEs. Fig. 1b depicts the indium consumption in mg/W vs PCE for reported tandem cells from 2015 to 2025. We reveal that reported high-PCE tandems currently use >1 mg/W indium, far above the <0.064 mg/W required for the target >3 TW/yr production [2]. We highlight options to reduce or eliminate indium in future TCE for tandems, including improved soft-deposition, nanophotonics, hybrid nanocomposites, and progress in DFT-guided discovery of new materials. These could overcome the mobility, stability and optical coupling limitations of current alternatives. Overall, the roadmap presented is intended to guide the PV community to identify TCEs capable of enabling >40% PCE perovskite-silicon tandems and >50% PCE multi-junction tandem devices.

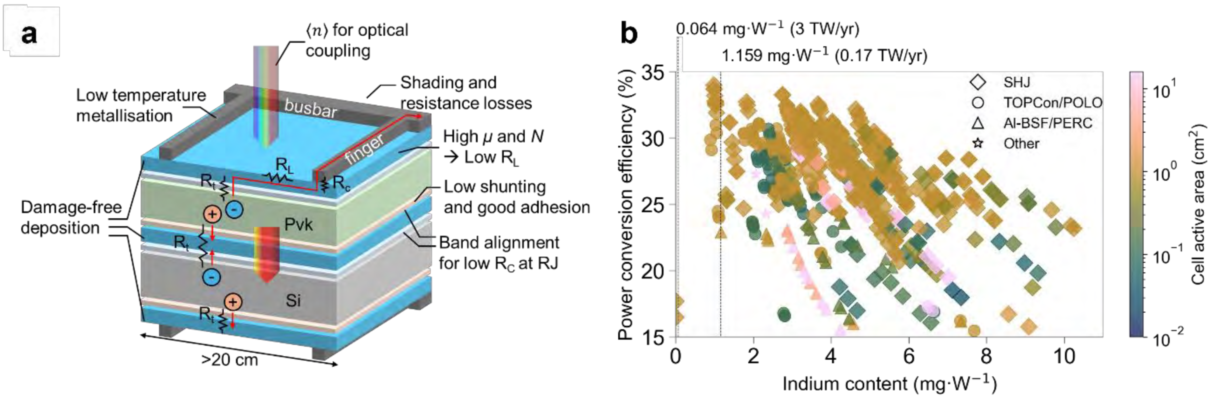

Figure 1 a) Losses induced from TCEs in 2T perovskite-silicon tandems. b) Indium content per watt generated in literature reported 2T perovskite-silicon tandem cells.

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Development of Multifunctional Anti-reflection Coatings for Space Photovoltaics

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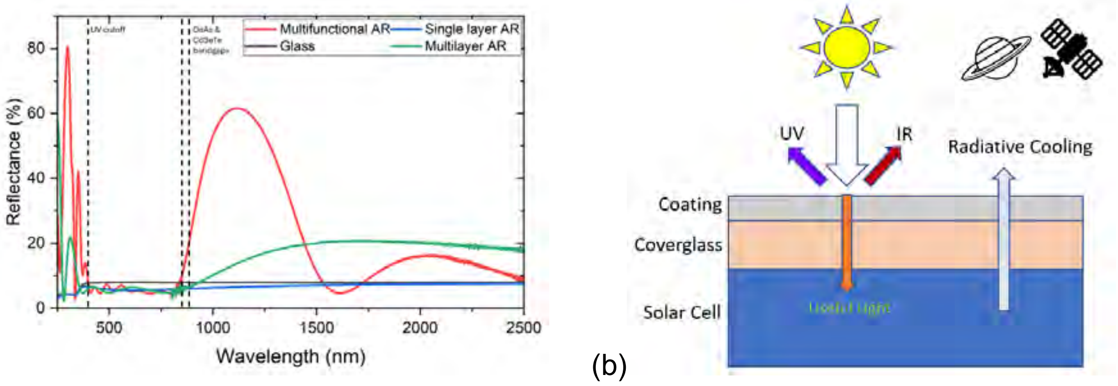
The vast majority of all photovoltaics (PV) modules, for both terrestrial and space applications, include some form of cover glass in their structure. Coatings applied to the front surface of the cover glass can be designed to address many problems, such as reflection losses, soiling, and even thermal management of the module. Typically, a single-layer antireflection (AR) coating is applied to most cover glass, often porous SiO_2 or MgF_2. These coatings are effective at reducing reflection but lack durability and do not provide additional functionality. [1]

Multilayer structures, made up of alternate layers of differing refractive index, can be used to address durability concerns whilst offering this additional functionality, such as reflection of sub-bandgap photons to provide passive cooling. Cooling of solar modules is crucial because solar cells become less efficient at higher operating temperatures. This is important for terrestrial applications, but even more so in space, with higher temperatures and fewer cooling pathways available. The space sector is also seeing a huge increase in attention, with exponential increase in satellite launches and the interest in space-based solar power, both of which will require significant increase in solar deployment. This increase in deployment is driving attention towards lightweight, low-cost PV such as CdTe and ultra-thin GaAs.

This submission shows the development of multilayer coatings to include AR and sub-bandgap reflection to provide passive cooling for both single-junction GaAs and CdTe-based devices for use in space applications, deposited on ultra-thin radiation tolerant coverglass. The coatings have excellent durability, with terrestrial applications in addition to space. Figure 1(a) shows the measured reflectance of multiple coating types – single layer AR, multilayer AR, and multilayer AR plus sub-bandgap and UV reflection to provide passive cooling, by reflecting photons that are not generating carriers and only heat the cell. The separate regimes for both GaAs and CdTe/CdSeTe solar cells are also shown by the dotted lines. Figure 1(b) shows a simplified schematic of the operation of the multifunctional coating for space solar cells. Thermal modelling predicts a temperature reduction of up to 14K for a GaAs cell using the multifunctional coating, alongside a reduction in weighted average reflectance of 2.5%.



(a) (b)

Figure 1 (a) Measured reflectance of the multiple coating types, (b) a simplified schematic of the multifunctional coating operation

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1. Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

Detection and identification of vacancy-related point defects in photovoltaic antimony selenide

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Antimony selenide (Sb_2Se_3) has an optimal bandgap and absorption coefficient for thin film solar cell applications and comprises earth abundant elements. The rate of increase in reported power conversion efficiencies has slowed due to a persistently large open circuit voltage deficit attributed to detrimental concentrations of point defects. Here we use depth-profiling positron annihilation lifetime spectroscopy to study Sb_2Se_3 crystals and thin films.

An implanted positron thermalizes rapidly then will eventually annihilate with an electron resulting in the emission of two 0.511 MeV annihilation photons. Two-component Density Functional Theory (TC-DFT) calculates the perfect lattice positron lifetime to be 257 ps. Neutral or negatively charged vacancy defects are strong traps for positrons and a positron localized at a vacancy defect site has a longer lifetime. TC-DFT calculations were also performed for the possible monovacancy configurations obtained by Wang *et al.* [1]. It was found that the –2 charge state Se vacancy lifetimes are in the range ~302 – 311 ps, while the –3 charge state Sb vacancy lifetimes are calculated to be in the range ~314 – 330 ps [2].

Experimental measurements on a series of p-type, n-type (e.g. Fig. 1) and insulating samples returned positron lifetime component values that clearly showed trapping to vacancy defects. Several n-type samples exhibited positron lifetimes consistent with trapping to –2 charge state Se vacancies [2]. The spectra from p-type samples were consistent with no trapping to vacancy defects and an experimental value for the perfect lattice state lifetime of 260(6) ps was obtained. Positron lifetimes longer than the calculated monovacancy values were also measured. DFT and TC-DFT calculations of possible divacancy defect configurations were performed and the resulting positron state lifetime values were found to be consistent with these longer experimental lifetime values.

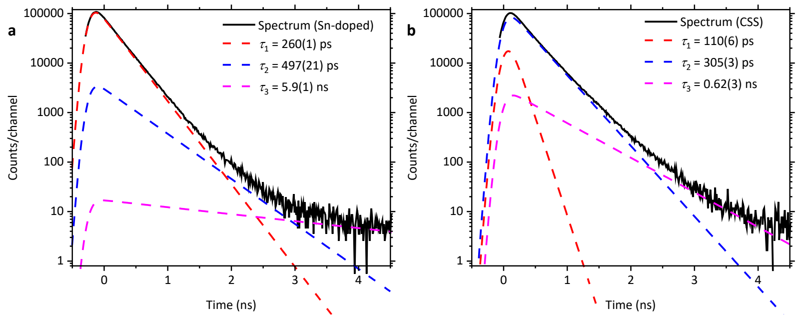

Figure 1 Experimental positron lifetime spectra. a) p-type, Sn-doped, Sb_2Se_3 crystal. b) CCS n-type conductivity Sb_2Se_3 thin film.

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Thermochemical processing of Sb_2S_3 nanorod inks: anion exchange pathways to Sb_2Se_3 absorbers for tandem photovoltaic applications

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Antimony chalcogenides Sb_2S_3 ($E_g \approx 1.6$–1.7 eV) and Sb_2Se_3 ($E_g \approx 1.0$–1.2 eV) offer complementary bandgaps suitable for tandem photovoltaics. Detailed balance calculations [1] predict efficiency limits approaching 42% for two-junction tandem devices; however, in this bandgap pairing, current-matching constraints in two-terminal (2T) architectures reduce practical efficiency relative to four-terminal (4T) designs. This motivates precise experimental control over absorber composition and bandgap to enable tandem-relevant device integration.

We demonstrate that a single hot-injection-synthesised Sb_2S_3 nanorod ink can be thermochemically retained as the sulphide phase or converted to the selenide phase through controlled chalcogen annealing. Films were spin-coated onto glass, Mo, and Mo/NiO substrates. Systematic mapping identified processing windows: sulphurisation at 350–400 °C preserves near-stoichiometric S:Sb ≈ 1.5, while temperatures exceeding 500 °C induce Sb-rich compositions due to sulphur evaporation. Selenisation at 450 °C for 90 min achieves complete S→Se exchange on glass substrates, while Mo substrates require lower-temperature, extended-duration selenisation (360 °C for 120 min) to balance conversion efficiency against $MoSe_2$ formation.

Selenisation yields near-complete S→Se exchange, with residual sulphur ~2 at.% for optimised samples. UV-Vis/Tauc analysis demonstrates the bandgap shift from $E_g \approx 1.6$ eV (as-deposited Sb_2S_3) to $E_g \approx 1.0$ eV (selenised Sb_2Se_3), validating spectral complementarity for tandem integration. Raman spectroscopy confirms phase-pure Sb_2Se_3 with characteristic modes at 97, 123, 155, and 186 cm^{-1} [2]. FIB cross-sections reveal columnar grain morphology with film thickness of approximately 2 μm, suitable for vertical carrier extraction. EDS with Mo Lα/S Kα deconvolution confirms Se:Sb ≈ 60:40 with residual S below 2 at.% for optimised samples.

A 20–30 nm NiO interlayer on Mo reduces residual sulphur toward 1 at.% while suppressing excessive $MoSe_2$ formation, positioning Mo|NiO as a device-ready back-contact platform. The optimised selenisation protocol (360 °C/120 min/2 Se pellets) yielding 2% residual sulphur emerges as the primary bottom-cell candidate based on combined compositional, morphological, and crystallographic assessment.

These results establish reproducible thermochemical processing windows for antimony chalcogenide absorbers and demonstrate that a single solution-processed Sb_2S_3 nanorod ink can access both sulphide (Sb_2S_3) and selenide (Sb_2Se_3) compositions through controlled anion exchange. The ability to tune absorber composition, phase purity, and morphology via post-deposition processing highlights the versatility of this ink platform for future integration in tandem photovoltaic architectures.

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1. Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

Ion Beam Analysis for Quantifying Hydrogen, Radiation Effects and Interfaces of Advanced Photovoltaic Materials

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Understanding light element behaviour, interface evolution and degradation is pivotal for improving next-generation photovoltaics (PV). At the Surrey Ion Beam Centre (SIBC), we use complementary ion beam analysis techniques, most notably Time-of-Flight Elastic Recoil Detection Analysis (ToF-ERDA) and Rutherford Backscattering (RBS), to obtain compositional depth profiles across a diverse range of PV materials. Offering matrix independent depth profiling all the way to the lightest elements, unlike other techniques which suffer from matrix effects and calibration challenges.

In silicon PVs, we used ToF-ERDA to provide unambiguous quantification of hydrogen in key surface passivation dielectrics; SiN_x, AlO_x and Al-doped ZnO (AZO) [1]. Showing a clear trend with hydrogen redistribution aligning with performance degradation after high temperature annealing. Monte Carlo ERD (MCERD) simulations were used to analyse double layer stacks and distinguish overlapping signals from Si and Al to enable precise interface analysis, such as the AZO/AlO_x stack shown in Figure 1.

For wide band gap perovskites, which are promising for space PV, the behaviour of their light element organic cations under proton irradiation remains unclear. ToF-ERDA was used to quantify compositional changes in Cs/formamidinium (FA) perovskite films following 80 keV proton irradiation, also carried out at the SIBC, equivalent to >300 years in low Earth orbit [2]. The depth profiles showed clear H, C and N depletion, with a $PDAI_2$ passivation layer suppressing this organic cation loss; demonstrating an effective method of improving perovskite radiation stability.

In addition, we used a multi modal approach combining ToF-ERDA and a new cluster ToF-SIMS tool to characterise organic PV (OPV) thin films. ToF-ERDA provided matrix-free atomic compositions while Ar cluster SIMS delivered molecular level information. This complementary analysis revealed the degree of mixing between polymers in layer-by-layer and bulk heterojunction OPVs.

These ion beam analyses provide quantitative, depth resolved insights needed to guide the development of robust, high-performance PV devices.

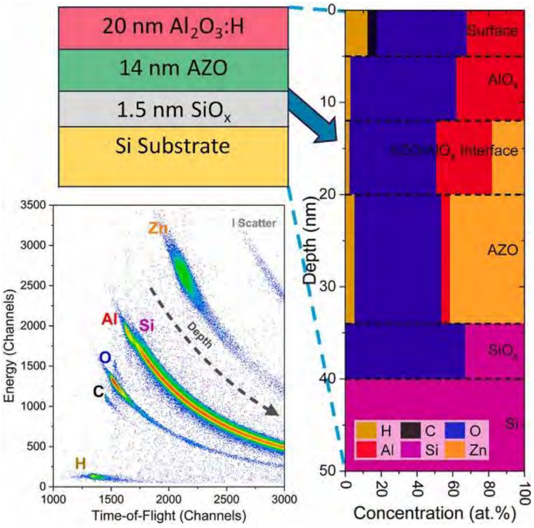

Figure 1. ToF-ERDA for AZO/AlO_x sample. Upper left shows expected growth, lower left shows ToF-E histogram and right shows elemental depth profile obtained.

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6. Photovoltaic systems, solar irradiance and monitoring, policy, sustainability, market development and life cycle analysis

From lab to reality: how non-AM1.5 conditions shape the future of perovskite and organic solar cells[1]

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The power conversion efficiencies (PCEs) of perovskite and organic photovoltaic (PV) devices under AM1.5 standard test conditions have improved rapidly, but their real-world energy yield remains poorly characterised. Standard tests often fail to capture the combined effects of temperature, irradiance and spectral variability that dominate outdoor operation and ultimately determine system-level performance.

This study explores the competitiveness of emerging PV technologies compared to silicon-based PVs by integrating device-specific performance data into energy yield models using historical climate datasets from locations around the world. Our analysis demonstrates that favourable temperature coefficients and spectral responses allow perovskite and organic PVs to achieve higher energy yields in certain climates than their AM1.5 ratings would predict. Indeed, the changes in performance due to real world operation are similar in magnitude to the incremental improvement in record cell efficiencies under AM1.5 conditions. These advantages narrow performance gaps or even achieve parity with silicon PVs in some specific climate regions, and our findings indicate that, in certain equatorial regions, perovskite PVs can already achieve near parity with silicon PVs under real operating conditions by narrowing the standard test condition gap from about 4.8% to 1.5%. Our findings underscore the critical need for comprehensive non-AM1.5 characterisation to improve energy yield predictions, optimise device design for real-world conditions, and enhance the competitiveness of emerging PV technologies.

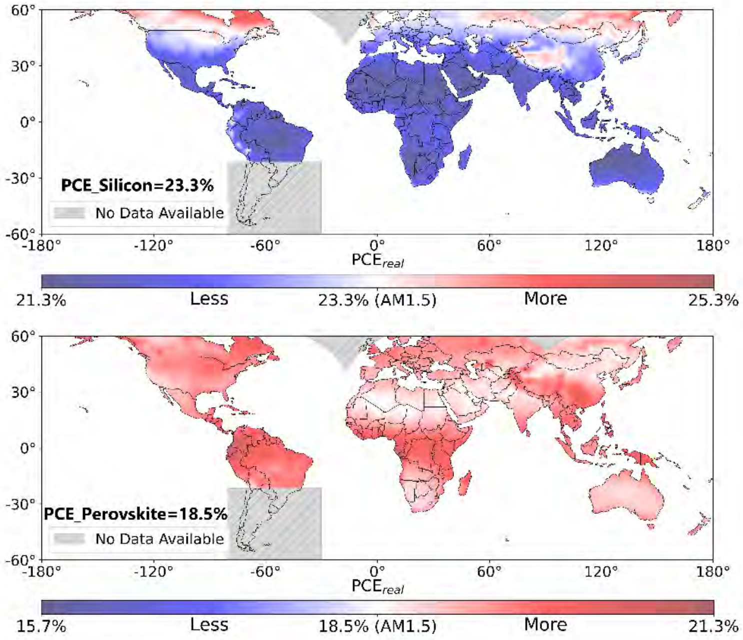

Figure 1 Predicted PCE$_{real}$ compared to PCE$_{STC}$ for silicon PV (upper) and perovskite PV (lower) across the world in 2019.

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Graded AZO/Al_2O_3 hole selective passivating contact for silicon heterojunction solar cells

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Aluminium-doped ZnO (AZO)/Al_2O_3 passivating contacts have been proposed as an efficient way to extract carriers in silicon solar cells [1]. In this work, we propose a possible solution to difficulties encountered in conduction band to valence band alignment in such contacts based on grading the doping in the AZO.

Silvaco TCAD simulations indicate that a 1%/3% AZO stack generates a significant energy barrier of 0.3 eV for holes, and draws electrons to the interface with the Al_2O_3 for recombining with holes from the silicon across the 1 nm Al_2O_3 tunnelling film (Fig.1(a)). Compared to ZnO/Al_2O_3, the 1%AZO/3%AZO/Al_2O_3 structure boosts tunnelling current under forward bias (I_F) by up to 4 orders of magnitude due to better band-edge alignment (Fig.1(b)). Grading the AZO doping suppresses current under reverse bias (I_R), yielding further improvements in I_F/I_R ratio (Fig.1(c)).

The first step in experimentally realising such a contact is to achieve good surface passivation through atomic layer deposition (ALD) of an ultra-thin Al_2O_3 film. Previous studies indicate that surface pretreatment optimisation is key to obtaining good quality ALD layers [2]. Here, we demonstrate that a 7:1 HF etch of n-type Si wafers (Cz, 1-5 ohm.cm) before the ALD process results in better passivation than using 20:1 HF (Fig.2(a)). Furthermore, among ultra-thin Al_2O_3 films (1-2 nm), 1.7 nm is an optimised choice, offering acceptable effective lifetime and thus a relatively well-passivated surface. We show that tuning the 7:1 HF etch time to balance surface roughness and cleanliness results in subsequent ALD ultrathin layers conferring effective lifetimes of >1 ms (Fig.2(b)), with uniform passivation achieved across most of the wafer surface (Fig.2(c)). Work is ongoing to add graded AZO to realise the full passivating contact.

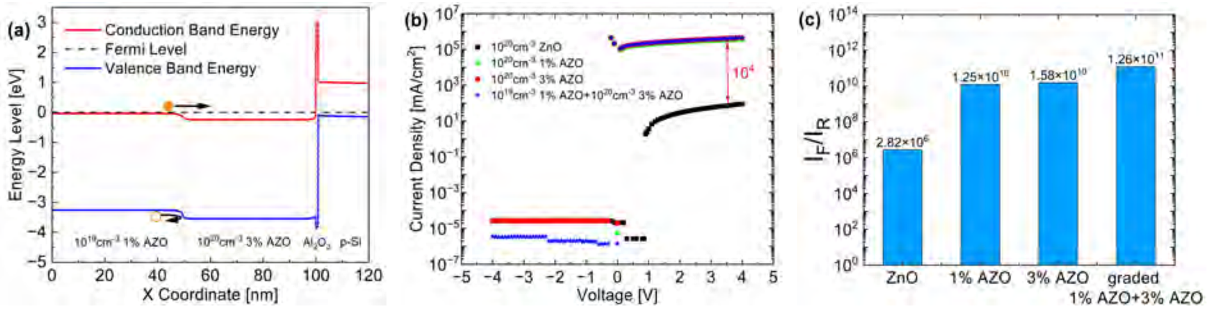

Fig.1 **(a)** Equilibrium band energy diagrams of 1%AZO/3%AZO/Al_2O_3 stack. **(b)** Simulated current density-voltage curve. **(c)** Ratio of forward current and reverse current of the four contact structures.

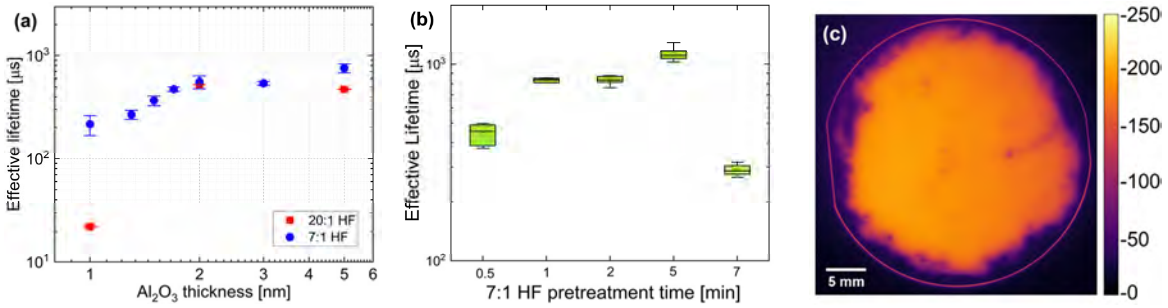

Fig. 2 Effective lifetime (at $\Delta n = 10^{15}$ cm^{-3}) of n-type Si wafers with **(a)** variable Al_2O_3 thicknesses under different pre-treatments and **(b)** 1.7 nm Al_2O_3 under different 7:1 HF pretreatment times. **(c)** Photoluminescence (PL) image of the 1.7 nm Al_2O_3-coated wafer after 5 min 7:1 HF etching.

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5. Perovskite, organic, tandems and DSSC photovoltaics

A-site Cations Engineering of Quasi-2D Passivation Layer for Efficient and Stable Perovskite Solar Cells

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Three-dimensional/Two-dimensional (3D/2D) lead halide perovskite represents a promising photovoltaic architecture, demonstrating high power conversion efficiency (PCE) and enhanced operational stability. [1,2] However, a comprehensive understanding of their interfacial properties at 3D/quasi-2D heterojunctions [1,3], particularly for phase-pure quasi-2D perovskites (n = 2), and the impact of A-site cations at the interface and on device performance remains limited. In this work, we design and synthesise a series of quasi-2D perovskites ($(PA)_2APb_2I_7$) through systematic A-site cations modulation. The structural analysis reveals that the quasi-2D perovskite crystals align with the underlying 3D perovskite, thereby promoting a horizontally oriented structure. These highly ordered thin films act as passivation layers, reducing trap density and facilitating efficient charge transport. By leveraging these interfacial improvements, the modified $3D/PA_2FAPb_2I_7$ solar cells achieve higher PCE than their 3D counterparts. Our study provides fundamental insights into the role of A-site cation engineering in directing crystal alignment, defect passivation, and paving the way for stable, high-efficiency perovskite solar cells.

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Hydrogen in atomic layer deposition-grown aluminium oxide films for silicon surface passivation

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Surface passivation reduces charge carrier recombination in semiconductors which, in the case of silicon, is pivotal to improving solar cell conversion efficiency. Passivation is typically achieved with dielectrics, and atomic layer deposition (ALD) of aluminium oxide (Al_2O_3) is used in >60 % of solar cells fabricated today [1]. Al_2O_3 offers excellent passivation, with achievable surface recombination velocities ≪1 cm/s [2]. Understanding the mechanisms underpinning this passivation has attracted considerable interest [3], with particular focus on the role of post-deposition treatments. Al_2O_3 passivation is attributed to the presence of negative fixed charges and good chemical passivation. Chemical passivation is thought linked to interfacial properties, *e.g.,* an interfacial oxide between Al_2O_3 and silicon [2] or the presence of hydrogen [4]. Hydrogen is believed to be incorporated into Al_2O_3 during the deposition process, arising from either the H/OH-terminated silicon substrate or reactants used in film growth.

We have used time-of-flight elastic recoil detection analysis (ToF-ERDA) to depth-profile hydrogen concentrations in Al_2O_3 films grown by ALD, and correlate these with effective lifetime measurements. ToF-ERDA reveals hydrogen concentrations are unchanged from as-deposited to when annealed up to the peak effective lifetime at an average level of ~1.2 at.%. As passivation starts to reduce at annealing temperatures >550 °C, average hydrogen concentration reduces to ~0.5 at.%, with no detectable increase in hydrogen in the silicon. If the Al_2O_3 film is considered as two regions – near-surface and near-interface – then below the optimal activation temperature, hydrogen concentrations are greater near the surface than the interface, a trend which is reversed when annealing above the optimal temperature.

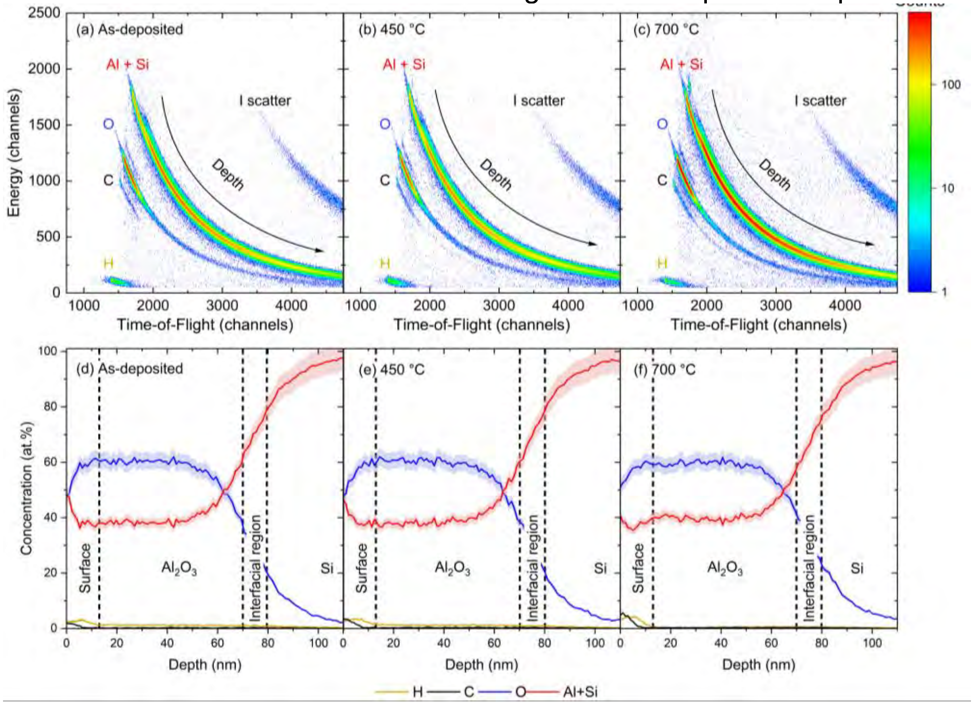

Figure 1: ToF-ERD histograms and elemental depth profiles for 75 nm Al2O3 on Si, (a, d) as-deposited, and annealed at (b, e) 450 °C and (c, f) 700 °C.

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The electronic and chemical properties of silicon/zinc-oxide interfaces for nanolayer transparent electrodes in photovoltaics

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Functional indium-free transparent conductive oxides (TCOs) that can simultaneously provide Si surface passivation (i.e. suppressed carrier recombination), conductivity, and transparency are urgently needed to enable multi-TW scale single and multijunction Si-based photovoltaic solar cells. ZnO:Al (AZO) has great potential to fulfil this role, but doing so requires a greater understanding of its Si surface passivation properties, both chemical (defect density reduction) and field effect (minority carrier separation). No established analysis methods have elucidated how these mechanisms work at device-relevant Si-AZO interfaces, for example, how annealing with an AlO_x cap (which is required to form passivating AZO[1]), generates field-effect passivation. Here, we present synchrotron x-ray photoelectron spectroscopy (XPS) analysis to directly measure the impact of AlO_x processing on Si-AZO interfacial band bending (i.e. local field effect), for the first time. We show increased band bending with annealing for AZO capped with AlO_x, from **0.61 to 0.78 eV** (fig 1a & b, blue) but a decrease for an uncapped sample, from **0.69 to 0.28 eV** (not shown). This suggests that (since AlO_x blocks hydrogen effusion[1]) hydrogen has a role in the field-effect passivation mechanism at Si-AZO interfaces.

Indeed, correlating these XPS measurements with minority carrier lifetime (fig. 1c and d) **demonstrates a monotonic relationship** between band bending and passivation. By extracting Si-AZO interface charge dynamics, these results will enable quantification of chemical vs. field-effect passivation, and predict design rules for integrating passivating AZO into photovoltaic device structures.

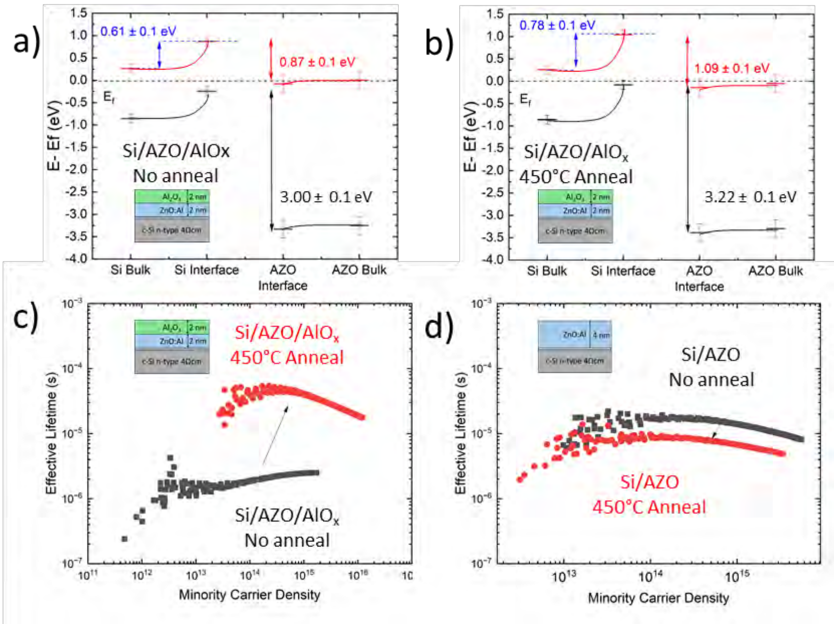

Figure 1. 1-dimensional experimentally-derived band diagrams for AlO_x-capped Si-AZO a) before annealing and b) after annealing. VBM positions (black) derived from Zn 3p and Si 2p core level positions, and CBM positions based on the Si and AZO bandgaps. Si-AZO valence band offsets are estimated in black, conduction band offsets in red, and band bending magnitude in blue. Photoconductance decay lifetime measured against minority carrier density for c) capped, d) uncapped Si/AZO, before and after annealing.

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5. Perovskite, organic, tandems and DSSC photovoltaics

Halide Perovskite Solar Cells for Space Applications

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Perovskite solar cells (PSCs) are drawing significant interest for use in space due to their low cost, high specific power, versatility and high radiation resistance. The space environment offers a harsh environment for PSCs including thermal shocks from the rapid temperature changes experienced during orbit, which is an environmental stressor that is very rarely examined.

This presentation will show the development of an accelerated thermal shock protocol to cycle PSCs between +/-80°C at a rapid ramp rate of 16°C/min for 100 cycles. This method was designed to replicate and accelerate the stresses created by the temperature variations found in low earth orbit (LEO) [1].

This protocol was tested using $FAPbI_3$ PSCs with varying concentrations (0-7%) of $MAPbBr_3$, to examine the thermal stability of each configuration under our protocol. Our results indicated that an intermediate level of 5% $MAPbBr_3$ most effectively prevented the formation of the non-photoactive δ-phase after thermal shock as well as smaller changes in both the hysteresis index and power-conversion efficiency.

This conclusion was then validated with a high-altitude balloon (HAB) test. The cells with varying $MAPbBr_3$ concentrations were flown to a height of 35km, well within the 20-100km near space environment. This test allowed for the cells to experience multiple space-like environmental conditions simultaneously, including low pressure, harsh temperature fluctuations, AM0 illumination and elevated UV. After the 2 hour 20-minute flight, the devices were recharacterised and the same conclusion from the thermal shock test was drawn, with the 5% device performing best. This was highlighted by the increased recombination losses within the 1% sample compared to the 5% device, seen by the larger decrease in EQE, as well as the greater stability of the Voc and FF throughout the flight.

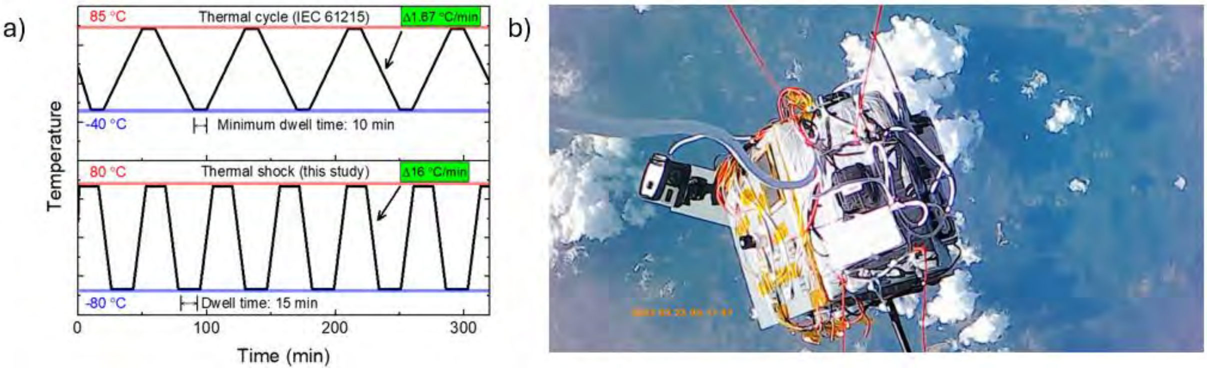

Figure 1: a) New space thermal shock protocol compared to IEC terrestrial tests, reproduced with permission from [1], Copyright RCS 2026, b) Gondola carrying cells at 35km during high altitude balloon test

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Poster Presentations

1. Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

Standardised Characterisation and Comparison of Indoor Photovoltaic Devices

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Indoor-photovoltaic (IPV) is becoming increasingly important in the context of the Internet of Things (IoT). However, the relative novelty of low-intensity light-harvesting PV technologies, together with the lack of standardised measurement set-ups and protocols across research laboratories worldwide, highlights the need for a common basis to compare IPV devices based on different technologies.

This work focuses on the standardised characterisation of five devices: an amorphous Silicon mini-module (a-Si, Panasonic); a c-Si cell (Swansea University); an OPV cell (Epishine AB); an OPV mini-module (Epishine AB); a KG5 filtered c-Si cell (ReRa Solutions) employed as the reference cell. The aim is to test these devices as specified by the indoor standard testing conditions (ISTC) in IEC TS 62607-7-2:2023 [1], and to compare their characteristic parameters. As a first step, the spectral response (SR) of the devices under test (DUTs) are measured and the associated spectral mismatch factor is calculated for each DUT with respect to the in-house calibrated c-Si KG5 reference cell and the measured light-source spectrum of the IPV simulator set-up.

The IPV simulator developed at NPL incorporates digital light processing (DLP) coupled with a digital micromirror device (DMD), delivering spectrally invariant intensity-adjustable light, while permitting to set illuminance levels based on the ISTC and correct them for spectral mismatch [2]. Finally, current–voltage (I–V) characteristics are measured and the corresponding device parameters are derived. These experiments are also conducted while controlling the DUT temperature and the uniformity of the light source across the sample plane.

The results demonstrate one of the first comparisons of IPV devices according to ISTC and provide an estimate of the sources and impact of measurement uncertainties associated with the set-up employed. Moreover, they highlight the importance of accounting for multiple factors when reporting efficiencies and cells parameters, such as spectral mismatch and IPV light-source spectrum evaluation and its uniformity. Such factors have affected results in previous intercomparison activities [3].

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Conference Topic: 6. Photovoltaic systems, solar irradiance and monitoring, policy, **sustainability,** market development and life cycle analysis

Assessment of laser material interactions for improving end-of-life management of silicon solar photovoltaic modules using COMSOL modelling

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Renewable electricity generated using solar photovoltaic (PV) systems is well acknowledged as an indispensable constituent of climate change mitigation and adaptation, leading to global PV deployment exceeding 1TWp in 2022 [1]. Considering predicted solar waste of 8 million tonnes by 2030 and 78 million tonnes by 2050 [2], end-of-life (EoL) management of solar PV modules is critically important. As bill of materials, solar cell technologies, wafer/glass/module dimensions are varying rapidly [3], EoL management processes need to be adaptable to these changes. Laser processing has been considered [4,5] for separation of solar PV module layers experimentally; however, the precision and adaptability of the laser processes could be analysed more accurately by assessing laser-material interactions.

In this work, COMSOL Multiphysics is employed to model laser-assisted delamination of a glass-encapsulant-silicon stack, assuming ethylene vinyl acetate (EVA) as an encapsulant. The model utilised a moving Gaussian heat source to simulate the laser irradiation. The energy of the incident laser irradiation is absorbed in silicon (Si) and then distributed to adjacent EVA and glass layers at front side. The Figure 1 elucidates the resulting temperature evolution in each layer when the laser irradiation power is 500W and beam width is 0.2 mm. The temperatures observed in the Si layer are in sync with the temperature range reported in [6] during laser cleaving of Si wafer.

These simulation results will aid in defining optimal laser parameters for experimental work to accomplish delamination of end-of-life Si solar PV modules while preserving solar cell integrity, allowing scalable, high-value material recovery.

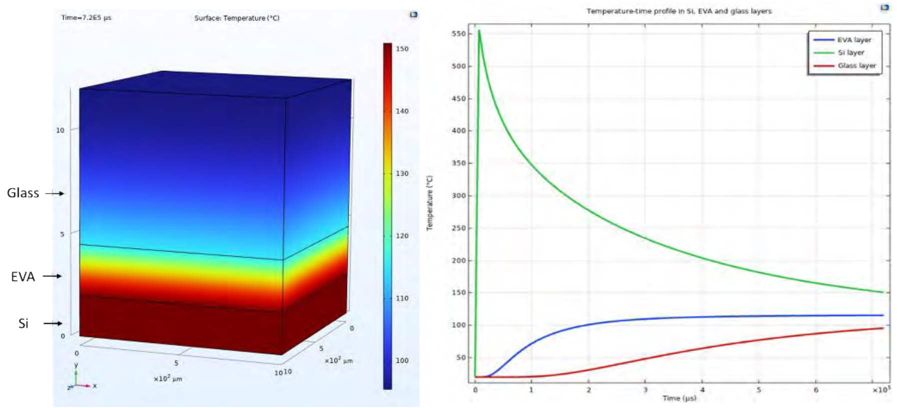

Figure 1: COMSOL predicted thermal response of the glass-EVA-Si stack under continuous wave laser heating. Along with the temperature-time histories from representative layers of glass, EVA and Si

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Development of Ecofriendly Organic Solar Cells with High Stability

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Organic photovoltaic (OPV) devices have been considered one of the most promising next-generation solar cell technologies due to their tunable bandgap, solution processability, low cost, semitransparency, and mechanical flexibility [1]. In addition, their compatibility with recyclable and biodegradable materials enhances their potential for sustainable and eco-friendly energy applications [2]. In recent years, with the continuous development of non-fullerene acceptors (NFAs), the power conversion efficiency (PCE) of OPVs has significantly improved, reaching as high as over 21% [1,3]. However, Stability is still the main challenge for the commercialisation of OPVs. The stability of OPVs is influenced by both external environmental factors and internal structural factors. Externally, environmental conditions such as light exposure, oxygen, temperature, and humidity can induce chemical degradation and morphological changes in the active layer, leading to device performance degradation [1]. Internally, spontaneous diffusion at the interfaces between the active layer, charge transport layers, and electrodes can also affect device stability and accelerate device aging [1].

In this study, we focus on enhancing the stability of PTQ10:Y12-based OPVs through the use of ecofriendly and low toxic liquid additives, such as p-anisaldehyde (P-anis) and γ-valerolactone (GVL) [4]. These liquid additives are expected to effectively enhance molecular ordering degree and crystallinity, thereby optimising the film morphology and promoting the formation of an ideal interpenetrating network structure within the active layer.

A comprehensive set of characterisation techniques will be employed to investigate the effects of liquid additives on the film morphology, device performance, and stability. Grazing-Incidence Wide-Angle X-ray Scattering (GIWAXS) will be used to analyse the molecular orientation, crystallinity, and stacking distance of thin films. J–V curve measurements will be performed to evaluate the photovoltaic performance of the devices, providing key output parameters such as open-circuit voltage (V_{oc}), short-circuit current density (J_{sc}), fill factor (FF) and PCE. Furthermore, Maximum Power Point Tracking (MPPT) measurements will be conducted to evaluate the operational stability under continuous illumination (AM 1.5 G, 100 mW cm^{-2}, N_2 atmosphere).

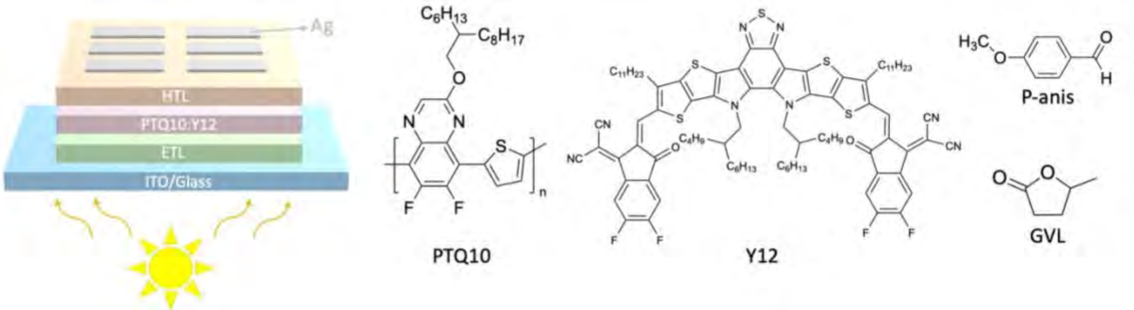

Figure 1 Schematic illustration of the inverted device architecture and the chemical structures of the photoactive materials (PTQ10 and Y12) and the liquid additives (P-anis and GVL) used in this study.

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Solvent dependent charge transfer dynamics in efficient and stable indoor copper-mediated DSSCs

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Indoor photovoltaics (iPVs) emerged as a reliable and sustainable power supplier to address the energy demands associated with the massive growth of Internet of Things (IoT) devices. Among them, dye-sensitized solar cells (DSSCs) have been evolving as the front runner, combining power conversion efficiencies (PCEs) >30 % under room light with safe materials, low-cost manufacturing, and pleasant aesthetics [1]. The drawback of DSSCs remains their electrolyte solution, which is primarily responsible for stability issues due to solvent losses through the sealant materials. Moreover, the preferred solvent for these electrolyte solutions is still nitrile-based solvents. The goal of using more abundant and sustainable materials in DSSC preparation reveal the need to find non-toxic but equally efficient solvents for the electrolyte solutions [2,3].

Solvents such as propylene carbonate (PC), γ-butyrolactone (GBL), and N-methyl-2-pyrrolidone (NMP) were considered for the first time as candidates for the electrolyte solvent in indoor DSSCs, and the photovoltaic (PV) performance of these devices was compared with that obtained with acetonitrile (ACN) and 3-methoxypropionitrile (MPN). Among them, PC and MPN-based devices exhibited PCEs >25 % under light intensities ranging from 300 lx to 1000 lx – **Figure 1a**. Therefore, these solvents are the most suitable for DSSCs subjected to low light intensities of ca. 300 lx, typically found in offices and homes. The results obtained from the photocurrent vs. applied potential (*J*-*V*) characteristics of these devices are supported by time-resolved photoluminescence measurements, which show a clear correlation between the donor number of the solvent and the modulation of excited-state dynamics. Both PC and MPN solvents displayed more stable PV metrics than ACN-DSSCs under continuous 1000 lx indoor illumination – **Figure 1b**. However, in comparison with MPN, the PC-based DSSCs benefit from the low toxicity and biodegradability of this solvent, which is considered a "green" solvent. Among other options, this work introduces PC as a sustainable and safe electrolyte solvent for the preparation of highly efficient and stable copper-mediated DSSCs that operate under indoor low-light conditions.

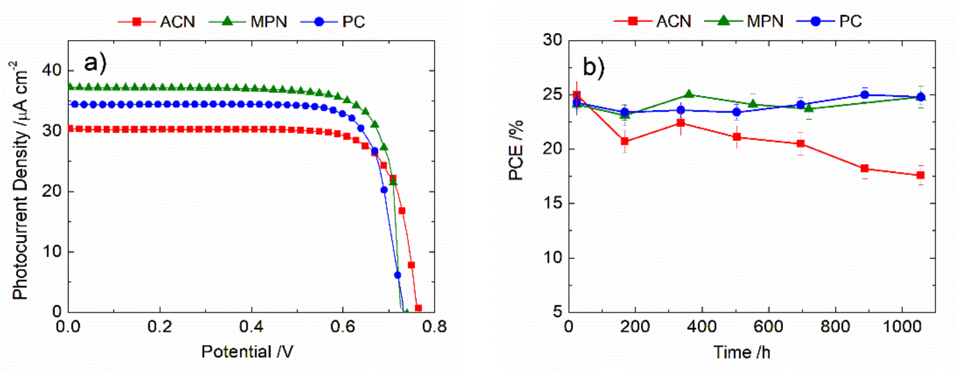

Figure 1 – Photocurrent vs. applied potential under 300 lx **(a)** and PCE vs. time under continuous 1000 lx **(b)** of DSSCs with different electrolyte solvents.

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Designing Interfaces and Understanding Ion Transport in Hybrid Perovskites for Optoelectronic Applications

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Hybrid halide perovskites offer exceptional optoelectronic performance, yet operational stability is frequently limited by defect formation and ionic migration, particularly at interfaces and extended defects. Here, we develop a robust first principles modelling framework for formamidinium lead iodide (FAPI) that establishes a validated bulk electronic-structure baseline and then extends to surface slab models, enabling physically consistent comparisons across geometries and terminations relevant to device operation. After establishing numerically stable computational settings through systematic convergence testing, we analyze the bulk electronic structure via band dispersion and projected densities of states. Bulk FAPI exhibits a direct bandgap of approximately 1.35 eV at the R point, with the electronic band structure shown in Fig. 1a, consistent with its suitability for photovoltaic applications. The projected density of states (Fig. 1b) indicates that the valence-band edge is dominated by I-5p states, while the conduction-band edge is primarily Pb-6p in character, reproducing the expected semiconducting fingerprint of iodide lead perovskites. Building on this bulk baseline, surface models of FAPI are constructed using a slab approach that exposes the (100) and (110) facets, with slab geometries generated in the Atomic Simulation Environment (ASE). For (100), PbI_2- and FAI-terminated surfaces are considered, while for (110) multiple candidate terminations are screened (including PbI, I, I_2, FA related terminations and a 2×1×1(I) reconstruction) to evaluate how surface chemistry and atomic motifs influence stability trends. Ongoing work extends these surface energy calculations to identify the most energetically favorable surface structures and the most stable terminations, followed by a systematic assessment of how termination-dependent relaxation affects structural stability and defect energetics. The modelling will then be expanded to include grain boundaries in order to quantify their impact on defect formation and ion-migration pathways that govern long-term device stability.

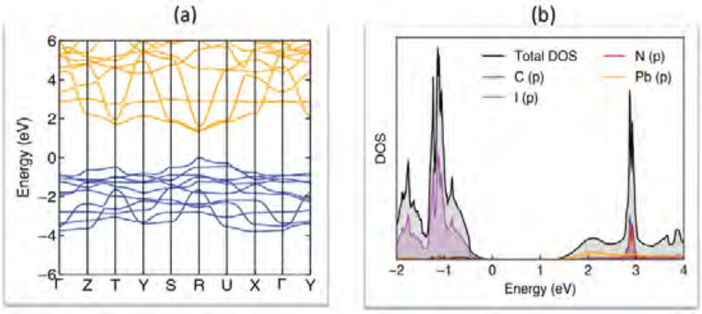

Figure 1: (a) Electronic band structure of FAPI. (b) Total and partial density of states (DOS) for FAPI.

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4. Crystalline silicon, Inorganic thin film, inorganic multijunction and concentrator photovoltaics

The effect of the sulphurisation rate on Bi_2S_3 films prepared by thermal vapour sulphurisation of bismuth precursors.

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Abstract:

Bismuth sulphide (Bi_2S_3) is a semiconducting material that has found potential application for thin film photovoltaics (PV). It has a bandgap of $1.2eV$ and its absorption coefficient surpasses $1\text{x}10^4 cm^{-1}$ within the IR to UV range efficiently absorbing most of the solar spectrum within $1\mu m$ [1,2]. Despite these advantageous properties, solar device performance is poor and can be linked to low crystallinity or high intrinsic carrier concentrations [3,4,5]. For PV applications, the films should have grain sizes comparable to the bulk carrier diffusion length and should be reasonably compact with a lower carrier concentration to that of the transport layer. Further the orientation must be controlled given its crystal structure consisting of $[(Bi_2S_3)_\infty]_2$ chains separated via van der Waals forces, with optimum carrier transport along them [6,7]. This study investigates the sulphurisation environment conditions of Bi_2S_3 films prepared from thermal vapour sulphurisation of sputtered bismuth films on FTO and glass to observe the effects on the structural and electrical properties. During sulphurisation two holding temperatures were used to separate the reaction and annealing conditions. All films were annealed at $540℃$ with two different reaction temperatures of $280℃$ and $325℃$. The sulphur dosage was also varied from $(5 \pm 0.5)mg$ to $(800 \pm 0.5)mg$ and all reactions used a bismuth film thickness of $(692 \pm 6.8)nm$. A range of different morphologies were produced from smooth compact grains to rough and loosely packed when increasing the sulphur amount. This also led to rapid decrease in the grain size from $(1.21 \pm 0.03)\mu m$ at $5mg$ to $(228.7 \pm 13.4)nm$ at $800mg$ for the samples on FTO. The same trend was seen on glass and when decreasing the reaction temperature to $280℃$ from $325℃$ showed rough samples throughout. The electrical properties have shown to be sensitive to the stoichiometry showing an increase in the carrier concentration from $(1.5 \pm 0.064)\text{x}10^{17} cm^3$ to $(6.3 \pm 0.044)\text{x}10^{18} cm^3$ with an increasing bismuth surplus of a few percent. The orientation of the films has shown to be influenced by the grain growth showing parallel alignment of the chains as the grain size increases. This trend was the same for those on FTO and glass. These findings have outlined the importance of controlling the chemical reaction rate of Bi_2S_3 films prepared by this method to produce films of better quality for use as an absorber layer in solar devices.

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Eco-friendly high open-circuit voltage organic solar cells enabled by PDI-derived acceptors

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Organic semiconductors have attracted considerable attention due to their light weight, mechanical flexibility, tunable energy levels, and compatibility with low-cost solution processing, and are regarded as a promising development direction for third-generation low environmental footprint photovoltaic technologies. However, the processing of high-performance organic photovoltaic (OPV) devices still relies on toxic halogenated solvents such as chloroform, which hinders large-scale manufacturing[1]. Developing high performing OPVs using environmentally friendly solvent systems is therefore a key pathway towards the commercialization of OPVs.

In this work, we systematically investigated OPVs based on perylene diimide (PDI) derived small-molecule acceptor processed from eco-friendly solvents. Benefiting from highly conjugated backbones, the acceptor enables efficient exciton dissociation under low energetic driving forces, resulting in high photocurrents. By constructing an asymmetric PDI dimer and incorporating bay-position N-annulation together with sterically bulky groups, we effectively suppressed the excessive aggregation associated with rigid planar backbones[2], thereby improving solubility and processability in non-halogenated solvents. The reduced aggregation also mitigated aggregation-caused quenching[3] commonly observed in PDI-derived solid films, enhancing the photoluminescence quantum yield and reducing non-radiative voltage losses in the devices.

Furthermore, HSPiP software based on Hansen solubility theory was employed to identify eco-friendly solvent combinations compatible with the designed acceptor system. The synergy between molecular design and solvent engineering enabled more controlled phase separation and crystallization during bulk heterojunction film formation, yielding bicontinuous morphologies with well-defined length scales and efficient charge-transport pathways. The devices based on this system achieved an open-circuit voltage exceeding 1 V, demonstrating a viable route towards enhanced OPV performance under eco-friendly solvent processing conditions.

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Enhancing Thermal Management in High Concentration Photovoltaic (HCPV) Systems Using Copper Oxide (CuO) and Graphene Oxide (GO) Nanofluids: Experimental Investigation and Performance Optimization

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High concentration photovoltaic (HCPV) systems represent a cutting-edge solar technology capable of achieving exceptional electrical conversion efficiencies by combining multi-junction solar cells with optical concentration. However, the intense solar flux concentrated onto the cell surface induces severe thermal loading, elevating cell temperatures beyond 90°C under operation - a condition that degrades efficiency, accelerates material aging, and compromises long-term reliability. Active thermal management is therefore not merely beneficial but essential for sustained high performance. The primary challenge in HCPV systems lies in mitigating excessive heat accumulation without compromising optical efficiency or system compactness. Conventional cooling methods often fall short under high concentration ratios, necessitating advanced thermal solutions that can efficiently extract heat while maintaining system integrity.

This study investigates the application of engineered nanofluids - specifically copper oxide (CuO) and graphene oxide (GO) nanoparticles suspended in a H_2O - as an active cooling medium for HCPV systems. Nanofluids at varying concentrations (0.05–0.5 wt.%) were synthesized and characterized (Fig.1). Initial results demonstrate that CuO nanofluid at 0.05 wt.% significantly enhances thermal absorption and heat removal from the solar cell surface. Further experiments were performed to evaluate higher concentrations of both CuO and GO nanofluids to optimize thermal conductivity and convective heat transfer.

Our findings confirm that nanofluid-based cooling is a viable and effective strategy for thermal regulation in HCPV systems. The integration of CuO and GO nanofluids not only suppresses operating temperatures but also holds promise for enhancing overall system efficiency and longevity. Future work will focus on optimizing nanoparticle concentration, flow dynamics, and long-term stability of nanofluids, with the goal of achieving synergistic improvements in both thermal and electrical performance. This research paves the way for scalable, high-efficiency HCPV systems capable of operating reliably under extreme solar concentration.

Fig1 . Nanofluid preparation process.

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Thermo-Opto-Electronic Analyses of Space-Based Photovoltaics

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By side-stepping external factors limiting terrestrial photovoltaics – including diurnal variations in the solar zenith and azimuth angles (which necessitate the use of solar tracking systems), the scattering of particular wavelengths in Earth's atmosphere, and the obstruction of light by clouds, dust, snow, and other meteorological phenomena – space-based photovoltaics (SBPVs) can generate more power at a more consistent rate. While SBPVs have already been powering satellites and space-stations for decades, future, utility-scale projects could provide power for Lunar bases, Martian colonies, and even Earth-based electrical grids (via wireless power transmission and rectenna arrays).[1-3]

The conditions encountered by SBPVs, however, are quite unlike those which terrestrial photovoltaics operate under, with high-energy particles and radiation bombarding devices continuously,[4] whilst temperatures may swing from below $-100^{\circ}\mathrm{C}$ in the shade to above $100^{\circ}\mathrm{C}$ in direct sunlight. In the latter case, remedial cooling may occur only via radiation and conduction, and not convection.[5] As a higher device temperature leads to an increased power derating, optimising SBPVs requires careful consideration and management of the unavoidable generation of heat (through charge carrier thermalisation and other mechanisms); alongside the usual considerations for optimising terrestrial photovoltaics like material choice (and its associated bandgap), device architecture, optical cavity effects in thin-film devices, and Ohmic losses due to parasitic resistances.

In the work presented herein, thermal, optical, and electronic simulations were combined to explore the performance of SBPVs. Using a finite-element approach, the influence of temperature profiles within the device on the refractive index, extinction coefficient, charge carrier generation profile, and heat generation profile was explored. While the finite element approach is agnostic with respect to material choice, these investigations were predominantly focussed on single-junction, thin-film cadmium telluride devices, with the power output of SBPVs being predicted in different case studies. Ultimately, these simulations help clarify routes towards higher-efficiency devices, enable comparisons with experimental measurements, and establish a foundation for future, modular enhancements to the device model.

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1. Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

A Low-Temperature, Low-Emission Solid-State Route to Barium Sulfide

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Barium sulfide (BaS) is an important precursor material in the synthesis of emerging barium-based semiconductors. [1] Conventional BaS production, however, relies on high temperature carbothermal or sulfidation processes exceeding 1000 °C, with associated CO_2 and SO_2 emissions that raise significant environmental concerns. [2] To date, successful methods that have lowered this temperature significantly often use highly corrosive hydrogen sulfide (H_2S).[3]

This work presents a solid-state synthesis route that substantially reduces both the thermal and environmental demands of BaS production. A finely milled mixture of barium hydroxide ($Ba(OH)_2.8H_2O$) and elemental sulfur is annealed under low pressure, achieving 90% conversion to phase-pure BaS at 500 °C. The low-pressure environment facilitates the continuous removal of H_2O vapour and trace SO_2 byproducts, inhibiting competing side reactions and sustaining a favourable sulfur partial pressure throughout the conversion.

Phase composition and conversion efficiency were characterised by X-ray diffraction with Rietveld refinement, corroborated by FTIR and Raman spectroscopy. Residual gas analysis confirmed the significant reduction in CO_2 and SO_2 output relative to conventional processes.

This approach opens a practical and scalable pathway to greener barium chalcogenide synthesis, eliminating the need for either extreme temperatures or hazardous reagents.

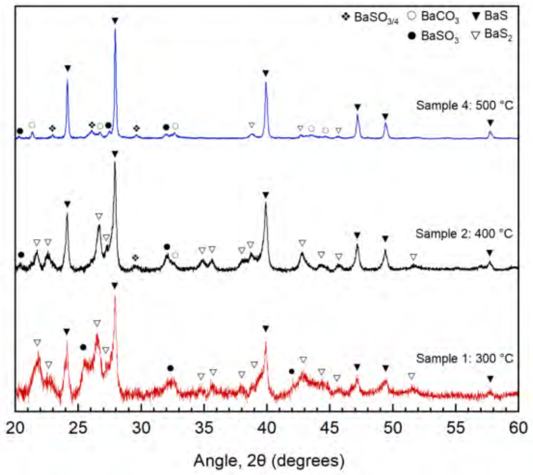

Figure 1 – BaS synthesis at 500 °C

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Reaction-Time Engineering of TiO_2 Nanostructures for Electron Transport Layers

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TiO_2 has shown great potential as a photocatalyst and electron transport layer (ETL) in thin-film optoelectronic devices [1–3]. In this work, we synthesised TiO_2 nanostructures (NSs) via a hydrothermal route on FTO-coated glass substrates using titanium butoxide (TBO) precursors in an acidic aqueous medium (HCl) at 200°C and investigated the time-dependent structural evolution. After 2h, sparse anatase nanoparticles (NPs) were observed, while after 4h anatase-dominated nanorods (NRs) formed with some nanoparticles with moderate aspect ratios. By extending the hydrothermal treatment to 12h; drives anatase to rutile transformation and the emergence of rutile-rich nanoflowers (NFs) with significantly increased aspect ratio. Prolonged growth up to 24h further develops rutile NF phases. A broad set of parameters was explored to control the NFs to NRs ratio.

Characterisation using XRD, Raman spectroscopy, SEM, EDS, AFM, and UV–Vis confirmed the correlation between growth time, phase transformation, surface roughness, aspect ratio, and interfacial coverage. The results suggest a time-governed growth mechanism involving initial nucleation of anatase nanoparticles from seed sites, followed by lateral aggregation into nanorods and flower-like rutile assemblies. From an application perspective, the nanorods and compact nanoparticles obtained at short growth times are well-suited for ETLs in Sb_2S_3 solar cells due to their favourable band alignment and interface quality. Additionally, seed-layer engineering and S/Nb doping offer further optimisation pathways for ETLs and photocatalytic applications.

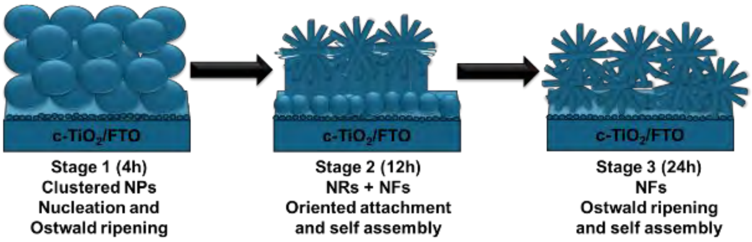

Figure 1: Stages during time-dependent hydrothermal growth at 200°C (c-TiO_2 is a 50 nm compact seed layer deposited by sputtering or ALD).

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Perovskite Photovoltaics in Space: Resilience Under Ion Irradiation

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The use of perovskite photovoltaics in space is an area of growing interest. This is driven by its numerous attractive properties such as high efficiencies, high specific power, flexible form factors and the potential for realising multijunction architectures at a much lower cost than current III-V technologies. While there are detailed studies on the influence of different stressors such as humidity and moisture for terrestrial applications, the research focus for perovskites in space has been mainly restricted to proton irradiation with promising outcomes [1].

Ion irradiation effects are another key area of significant concern for electronic devices operating from low earth orbit to deep space with charged particles such as electrons, and alpha particles leading to performance degradation or complete failure of these devices [2,3]. Solar flares are also known to generate alpha particles with high fluxes leading to rapid failure of devices unless appropriately engineered. Despite its importance, the influence of alpha particle irradiation on perovskite photovoltaics remains an area that is less well studied.

In this work, the effect of alpha particles on the stability of perovskite solar cells is discussed. We will discuss the influence of varying alpha particle energies and cumulative ion doses on the performance retention for an inverted p-i-n type architecture. The major sources for performance losses are identified and strategies for device architecture modification will be further discussed.

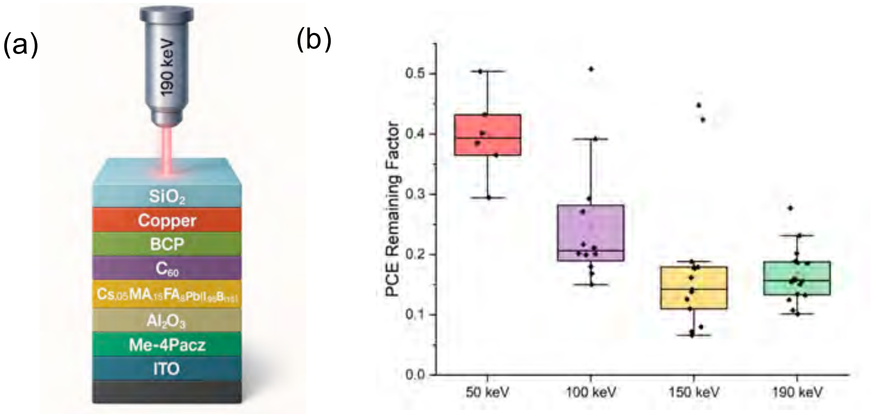

Figure 1 a) Schematic of device architecture and irradiation configuration of a representative perovskite solar cell. b) Power conversion efficiency remaining factor under different alpha particle energies.

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1. Perovskite, organic, tandems and DSSC photovoltaics

Fabrication of Laser Interconnected Solar Perovskite Modules

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Perovskite photovoltaic technologies have undergone rapid development since 2009, with current champion power conversion efficiencies (PCEs) of 27.3% [1]. Upscaling these devices provides many challenges and represents a critical barrier to commercialization. Laser scribed interconnects enable upscaling whilst maintaining high efficiencies by maximising module active area. However, the femto- or pico- second lasers typically used are expensive, counteracting the low-cost advantages of perovskite modules. Nano-second lasers are more affordable, however, the longer nano-second laser pulse results in increased material melting and heating. This heating can induce defects within the perovskite, impacting the quality of the fabricated module, demonstrating the importance of laser parameter optimization.

Combining this with the low-cost nature of perovskite precursors makes the module manufacturing process more accessible. This work will introduce the module fabrication and nanosecond laser scribing process, identifying rapid methods of analysing scribe quality. The challenges when designing and fabricating modules for glass, including laser parameters, inconsistencies and defects will be discussed, and the difficulties when transferring to roll-to-roll will be identified. This will enable efficient and affordable manufacture of solar modules.

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1. Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

Bulk and Microscopic Characterisation of Solar Cell Materials with Multimodal Spectroscopy

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Optical spectroscopy is employed routinely in the development of new photovoltaic (PV) materials and devices. Properties such as bandgap, carrier lifetime, and efficiency can be characterised via PL spectra, lifetime, and quantum yield. In the microscopic scale, combined Raman, PL, and FLIM are powerful tools to study structure and defects.

Stady-state and time-resolved, bulk and microscale experiments are often performed using different equipment. One of the challenges of PV researchers is carrying out these experiments in an efficient, reproducible manner.

This presentation will introduce multimodal setups for a full spectroscopic characterization of PV materials such as perovskites and organic solar cell devices. We will discuss the benefits of each technique and how to correlate the results.

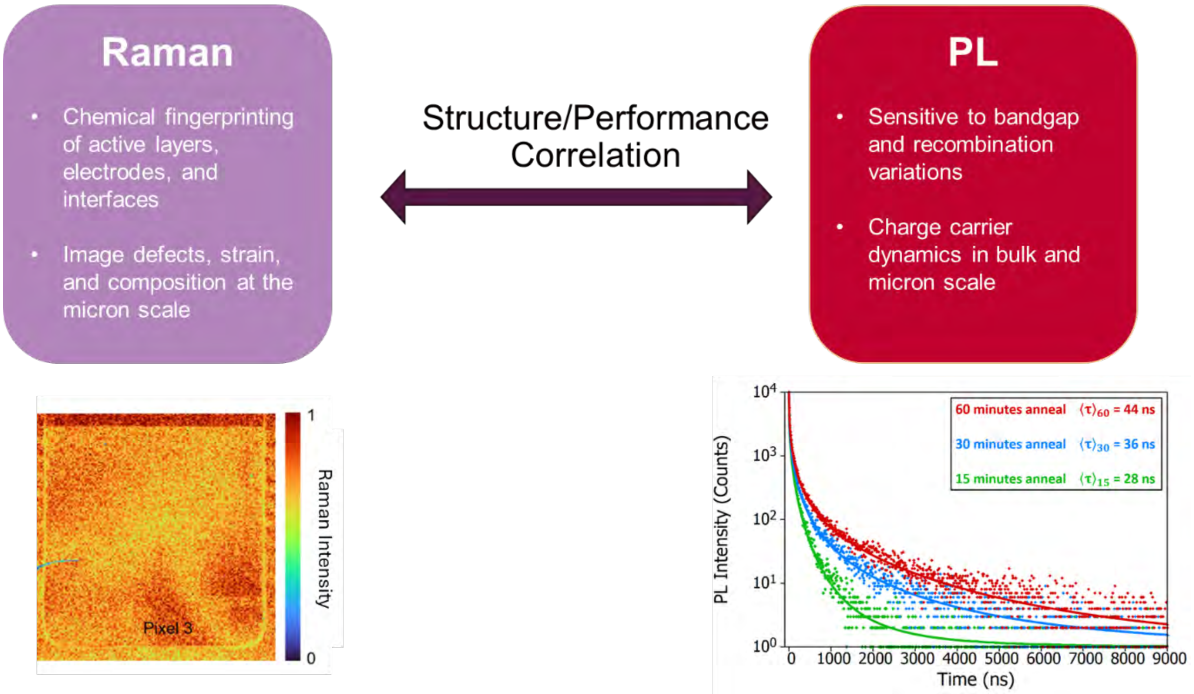

Figure 1 Raman intensity mapping of a solar cell and carrier lifetime measurement with time-resolved PL.

Sb_2Se_3 Photoreceiver Enabling Energy Harvesting and Optical Signal Transmission

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Antimony chalcogenides (Sb_2X_3, X = S, Se) have recently emerged as promising semiconductors for thin film solar cells due to their optimal bandgap (~1.1 to 1.2 eV), high absorption coefficient, earth abundance, and low toxicity profile.[1-3] The Sb_2Se_3 quasi one-dimensional [001]-oriented ribbon structure promotes anisotropic charge transport, which can be exploited for both photovoltaic conversion and high-speed photocarrier response, essential for data communication. While Sb_2Se_3 has achieved >10% efficiency in stable solar cells,[1] only limited studies have explored its use as a photodetector, and its implementation as a self-powered photoreceiver has not yet been demonstrated. This work establishes Sb_2Se_3 as a dual-function device capable of simultaneous photovoltaic power generation and optical signal decoding, meeting the bandwidth, scalability, and sustainability demands of next-generation IoT networks.

Figure 1 (a) shows the eye diagram obtained for a 1 Mbps On-Off Keying (OOK) signal, showing a peak-to-peak amplitude of 10mV and a well-defined eye diagram aperture that distinguishes the logical levels. The registration of 100k periods yields a signal-to-noise ratio (SNR) of 15.27 dB, and a corresponding bit error rate (BER) of 3.3×10^{-9}, as shown in Figure 1 (b). In the background of Figure 1, subset (c) illustrates the frequency response of the system, obtained by sweeping different frequencies sinusoidal tones across a range. The normalized amplitude (in dB) obtained in each case, present a −3 dB cutoff point at approximately 930.19kHz, defining the system bandwidth. This bandwidth agrees with the observed eye diagram performance at 1 Mbps, confirming the suitability of Sb_2Se_3 solar cells for optical wireless communication applications in IoT.

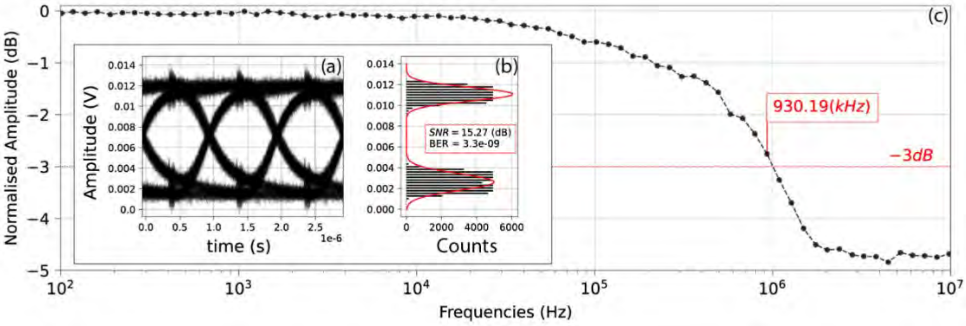

Figure 1: (a) Eye diagram obtained when transmitting pseudorandom data in OOK NRZ format at 1Mbps, (b) the histogram obtained from the sampling process over 100000 counts and (c) the frequency response test over the Sb_2Se_3 solar cell, indicating the -3dB bandwidth.

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6. Photovoltaic systems, solar irradiance and monitoring, policy, sustainability, market development and life cycle analysis

Improving PV system degradation forecasting using machine learning ensembles and a combination of real and synthetic system data

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An important financial risk to potential investors in solar photovoltaic (PV) projects is the energy losses from the degradation of PV modules over the lifetime of a project. Moreover, there is currently no industry-standard methodology for predicting PV module degradation rates [1]. The industry currently employs a mixture of publicly available tools, manufacturer's datasets and literature insights to forecast the degradation of pre-operational projects and to derive the degradation of existing projects from operational data. On the other hand, there is a growing library of data of PV projects in every PV system company's portfolio. These can be used to build predictive degradation models.

In this work, we propose a data-driven method for forecasting degradation rates of PV systems using real datasets, synthetic datasets, and machine learning. Ensembles of regression models are trained on real PV plant performance data (irradiance, temperature, output power, availability, location) and further fine-tuned using high-quality, synthetically generated (physical modelling) PV system output data. These ensembles are then aggregated together and used to forecast the performance and degradation for real PV systems, only using irradiance and temperature data. Predictions are accompanied by confidence intervals – generated using conformal prediction – that quantify model uncertainty. Using the above methods, we demonstrate accurate performance modelling and prediction that are validated with real PV system data.

This approach can potentially outperform physical modelling, while specific real datasets can be added in the training process to create location and system specific predictions for existing PV projects. These tools can be valuable for predicting the degradation rates for different PV systems and PV module technologies, even at a design and pre-operational stage, thereby reducing investment risks and accelerating the pipeline of PV system development projects.

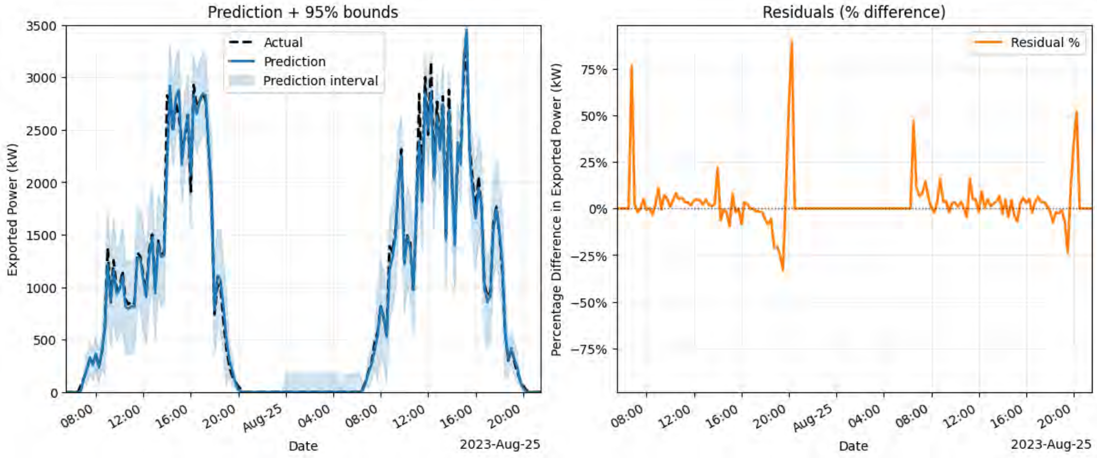

Figure 1. Results of our trained models on unseen real PV system data (actual). (Left) High temporal resolution model predictions for 2 days (prediction), with confidence intervals generated using conformal prediction (prediction internal). (Right) Residuals – percentage difference, with the spikes occurring at very low irradiance levels.

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Silicon Surface Passivation by ZnO/Al_2O_3 Stack with Controlled Interlayers

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Currently, high efficiency in crystalline-silicon solar cells is typically achieved by using passivating contacts such as those used in Heterojunction with Intrinsic Thin Layer (HIT) and Tunnel Oxide Passivated Contact (TOPCon) architectures to reduce recombination at the interfaces [1]. However, these cell architectures suffer from parasitic absorption, higher manufacturing cost, and involve toxic process gases. Transparent conductive oxides (TCOs), such as ZnO, have been explored as a promising candidate to reduce parasitic absorption due to high optical transparency, while offering electron selectivity [2]. Recently, it has been demonstrated that atomic layer deposited ZnO can also provide effective silicon surface passivation, which can be augmented by Al-doping of the ZnO film [3, 4]. Adding further to the advantages, ZnO also offers low sheet and contact resistivity [4], making it a compelling candidate for passivating contacts. In this regard, we examined silicon surface passivation using ZnO (0-80 nm)/Al_2O_3 (25 nm) stacks deposited by atomic layer deposition (ALD), with particular focus on the role of the interlayer formed between the ZnO and the silicon substrate (150 µm thick). The study was conducted using controlled interlayers formed by applying different silicon surface treatments, namely HF dip (to remove any native oxide) and oxides grown by chemical treatments (RCA1, RCA2, and NAOS) and UV-ozone exposure, which were characterised using X-ray photoelectron spectroscopy (XPS). The passivation quality dependence on the annealing temperature was investigated in the range of 400-600 °C in air for 30 min. Figure 1 demonstrates the effective lifetimes of ZnO/Al_2O_3 passivated silicon as a function of (a) annealing temperature and (b) ZnO thickness. The ZnO/Al_2O_3 stack can passivate the silicon surface with a peak effective lifetime attained with annealing at 475-500 °C. The interlayer formed by the NAOS (nitric acid) treatment provides the highest lifetime. The passivation quality is strongly dependent on the ZnO thickness, with the effective lifetime increasing as the ZnO thickness increases to 80 nm. The results clearly suggest that the silicon surface passivation by the ZnO/Al_2O_3 stack is strongly dependent on the interlayer, annealing temperature, and ZnO thickness.

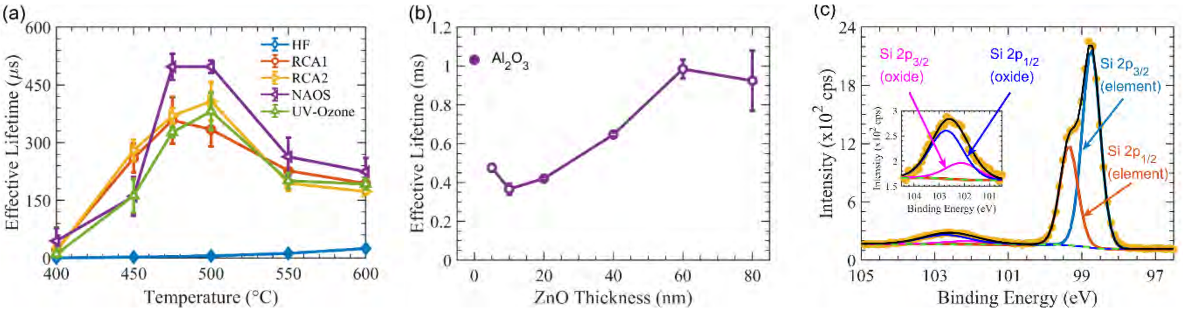

Figure 1. Effective carrier lifetime (at a minority carrier density of 10^{15} cm^{-3}) of 5 Ωcm silicon passivated with (a) ZnO (20 nm)/Al_2O_3 (25 nm) as a function of annealing temperature with controlled interlayers formed by different treatments (HF (no oxide), chemical (RCA1, RCA2, and NAOS) and UV-ozone oxides), (b) ZnO/Al_2O_3 (25 nm) as a function of ZnO thickness with NAOS treatment and annealed at 500 °C, and (c) XPS spectra of the silicon surface with NAOS treatment.

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1. Conference Topic

Development of novel small-molecule electron transport materials for tin perovskite photovoltaics

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Advancing tin perovskite photovoltaics requires identifying alternatives to conventional fullerene-based electron transport materials to increase the open-circuit voltage and device stability, whilst also reducing material costs. This poster describes a series of novel perylene diimide (PDI) and naphthalene diimide (NDI) small molecules with potential as electron transport and surface defect passivation materials for tin perovskite photovoltaics. Three approaches to utilizing these materials are being explored: (i) As a direct replacement for the fullerene electron transport layer.; (ii) As an ultra-thin defect passivation layer that is incorporated into the perovskite layer during its deposition.; (iii) As a replacement for the bathocuproine electron-extraction layer, which is known to be a source of device instability due to crystallization.

Figure 1 a) PVSAT-2026 Conference will take place at Newcastle

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The Development of Novel, Dopant-Free Hole Transport Materials for Perovskite Solar Cells

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With increased energy demand, research is turning its attention to methods of keeping up with these demands. Just over 5% of the world's electricity is produced through photovoltaic devices (PVs) with over 80% of this being produced from bulky crystalline silicon-based PVs containing finite resources. With these disadvantages of current photovoltaic technology, focus is being shifted towards lightweight alternatives, such as perovskite solar cells. These devices feature a metal-halide perovskite active layer with a direct band gap, allowing for an absorbing layer up to 500 times thinner than their silicon counterparts, drastically improving the number of applications. The main issue with perovskite solar cells (PSCs), however, lies in the reactivity of the perovskite active layer with water.

Hole transport materials (HTMs) are crucial for achieving high efficiencies in PSCs due to their ability to separate charge carriers generated in the perovskite active layer. Most commonly used HTMs require the use of hygroscopic dopants to increase their ability to carry these charges, introducing water to the perovskite layer, degrading it. This project looks into developing new dopant-free hole transport materials in an effort to increase the lifetime of the cells. This is initially done through computational screening methods to identify potential materials. Once suitable materials have been identified, these are synthesised and their optoelectronic properties tested. The computational screening suggested that 4 triphenylamine-based materials could be suitable candidates. While efforts to purify these materials had mixed success, a group of functionalised phthalocyanines also showed promise. These eight phthalocyanines varied the metal centre, as well as the amount of functionalization.

Once synthesised, the energy levels of the materials were calculated both in solution and in a thin film. These confirmed the computational data and indicated no issues for use in perovskite solar cells. While devices efficiency tests are still needed, the optoelectronic properties for the materials look promising.

Characterising hot carrier effects in ultra-thin III-V solar cells

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The efficiency of single Junction cells are rapidly approaching the Shockley-Quessier (SQ) limit, with one major energy loss being thermalisation[1]. In polar semiconductors like III-V materials this thermalization process occurs via the Frohlich interaction and occurs on the order of picoseconds, much faster than carrier extraction[2]. In this process,"hot" carriers with energy higher than the lattice lose this excess thermal energy by producing LO phonons until the carriers are at the same temperature as the lattice[2]. There are 2 main solar cell architectures which reduce this loss, Multi-junction solar cells and hot carrier solar cells (HCSC), with HCSC being more spectrally invariant, due to the lack of current matching requirements as there is only one absorber[1,2].

Hot carriers can always be observed in time resolved experiments, however it has also been observed in steady state experiments in nanostructure absorbers, or under high power densities[2,3]. The main method of observing hot carriers is via photoluminescence, in which the emission is related to the generalized Planck's equation to determine a temperature for the charge carriers[2,3]. This can be done in steady state experiments or time-resolved experiments to determine dynamics. While the carrier behaviour has been studied in many cases, the phonon behaviour in this situation has not been characterised extensively in literature. As information on the LO phonon behaviour gives more insight into the orgins of steady state hot carriers. Raman spectroscopy is a technique which allows the optical phonons to be directly probed, allowing a wealth of information to be accessed ranging from lifetimes, population, temperatures, carrier densities and electron-phonon coupling etc.

Steady state hot carriers are required for HCSC to function while many works have demonstrated hot carriers, many would not function as working solar cells, we demonstrate hot carriers in an ultra-thin GaAs solar cell. And show the enhancement of hot carriers via a changing electric field, and the effect of evaporative cooling on a hot carrier population. This work also explores the use of Raman spectroscopy to study hot carrier behaviour showing an inhibition of LO phonon production with increased carrier temperature.

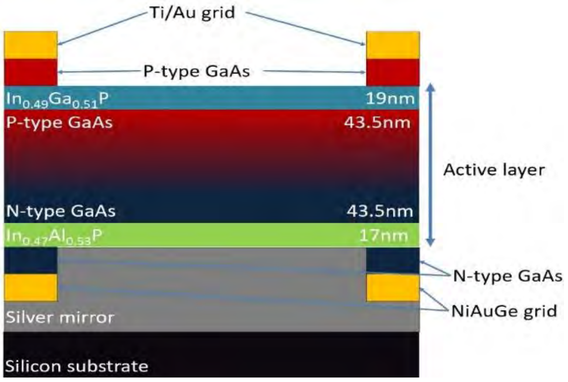

Figure 1: Diagram of ultrathin GaAs solar cell studied in this work.

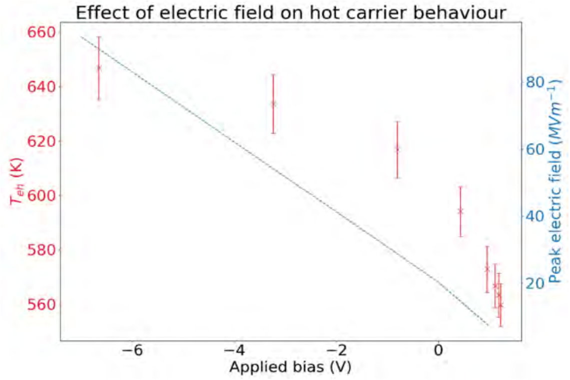

Figure 2: Hot carrier behaviour of device in figure 2 at different biases excited with a 727 nm laser and simulated peak electric field within pn junction at different biases.

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1. Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

Investigation of vacancy point defects in $CdSe_xTe_{1-x}$ semiconductors

A. Singh[1], D. Kuciauskas[2], M. Reese[2], M.O. Liedke[3], A. Wagner[3], R. Farshchi[4], B. Good[5], J. Becker[5], D.J. Keeble[1]

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The increase in CdTe solar cell efficiency from 22.1% (2015) to 23.1% (2024) is attributed to improvement in open-circuit voltage (V_{OC}), which now exceeds 900mV in polycrystalline devices. There is currently a focus on controlling reducing electronic disorder which requires further suppression of point defects. Anion vacancy disorder is considered to be of particular importance and strategies to reduce this are being developed [1]. In this work we apply depth-profiling positron annihilation lifetime spectroscopy, which has specific sensitivity to neutral and negatively charged vacancy defects to characterize $CdSe_xTe_{1-x}$ films.

Positrons thermalize within a few picoseconds and enter a Bloch state in perfect materials. A positron in a perfect lattice state will annihilate with an electron and the resulting positron lifetime is a characteristic of the material. Missing-atom, vacancy, point defects that are neutral or negatively charged with respect to the lattice localize positrons and have a lifetime that is longer than the perfect lattice state and is characteristic of the vacancy type.

Figure 1a shows a comparison between the positron lifetime spectra from an as-grown $CdSe_{0.2}Te_{0.8}$ film and a post-growth processed film. Two-component density functional theory calculations estimate the perfect lattice lifetime for CdTe to be in the approximate range ~290-305 ps. Figure 1c shows that the lifetime spectrum from the processed film is consistent with the dominant fraction of positron annihilating from the perfect lattice state. By contrast, the spectrum from the as-grown film (Fig. 1b) clearly exhibits trapping to neutral or negatively charged vacancy defects resulting in a dominant ~360 ps positron lifetime component.

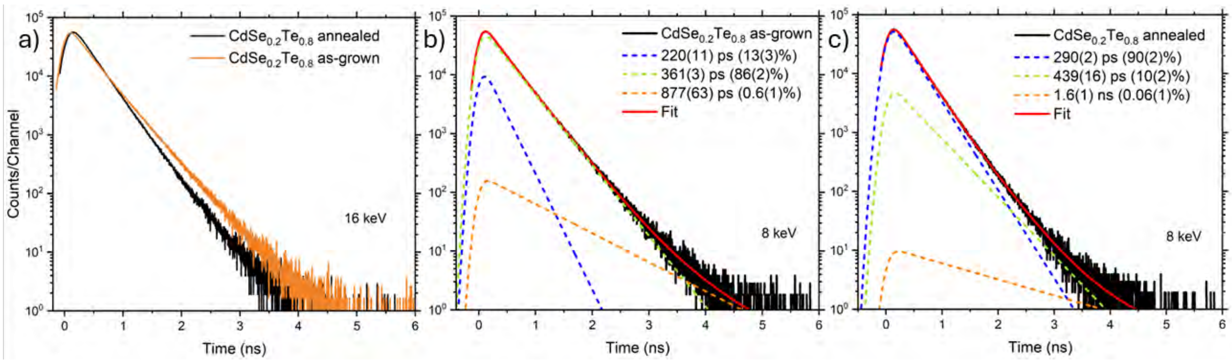

Figure 1 a) Comparison of positron lifetime spectra between as-grown and post-growth processed $CdSe_{0.2}Te_{0.8}$ films. Fit component analysis for b) as-grown and c) post-growth processed films.

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1. Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

Identification of vacancy-related point defects in inorganic perovskite halide semiconductors

A. Singh[1], J. Wiktor[2], M.O. Liedke[3], A. Wagner[3], K.S. Bayikadi[4], M. G. Kanatzidis[4], Y. Lu[5], T. Kang[5], G. Tumen-Ulzii[5], S.D. Stranks[5], Y. Kominko[6], A. Kanak[6], S. Yakunin[6], M.V. Kovalenko[6], D.J. Keeble[1]

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Wider bandgap inorganic perovskite halides are under development for photovoltaic applications. $CsPbBr_3$ is the material of primary interest. This work focuses on the detection and identification of cation vacancy point defects in $CsPbBr_3$ and $CsPbCl_3$. Single crystal $CsPbBr_3$ and evaporated $CsPbBr_3$ and $CsPbCl_3$ film samples are studied using depth-profiling positron annihilation lifetime spectroscopy.

An implanted positron thermalizes rapidly then will eventually annihilate with an electron resulting in the emission of two 0.511 MeV annihilation photons. In a perfect material the positronic density is delocalized (Fig. 1a) and the perfect lattice positron state has a characteristic lifetime value. Neutral or negatively charged vacancy defects trap positrons (Fig. 1b) and the localized state lifetimes are longer than the perfect lattice or bulk lifetime, and are characteristic of the particular type of vacancy defect. These positron state lifetimes can be calculated using two-component density functional theory (TC-DFT). He we report the positron state lifetimes for the perfect lattice and for the A-site, Cs, and B-site, Pb, cation vacancy defects for $CsPbBr_3$.

Experimental positron lifetime results (e.g. Fig 1c) are also reported. A positron lifetime component with a value of ~352 ps is systematically observed and is consistent with the TC-DFT calculated lifetime for the Pb vacancy. In addition, in certain samples a second longer, ~ 440 ps, lifetime component was also resolved and is in agreement with the calculated value for Cs vacancies. The results are consistent with previous TC-DFT calculations and experimental positron lifetime studies in $MAPbI_3$ [1] and $MAPbBr_3$ [2] that have observed positron trapping to Pb vacancies, and to A-site vacancies in $MAPbBr_3$ [2].

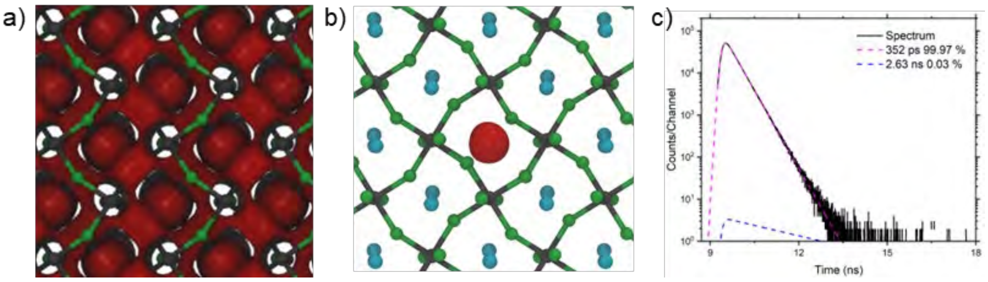

Figure 1 $CsPbBr_3$ positronic density for a) perfect lattice and b) containing a Pb vacancy, c) positron lifetime spectrum from a $CsPbBr_3$ single crystal.

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Enhancing Photovoltaic Efficiency through Coated V-trough Concentrators: Optical, Thermal, and Electrical Investigations

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Abstract:

In recent years, photovoltaic concentrator technologies have gained wide attention due to their ability to lower costs and enhance solar energy utilization across different regions. Their effectiveness is supported by the fact that concentrator photovoltaics (CPV) can significantly improve energy yield and support diverse applications. Among these, V-trough concentrators provide a simple and cost-effective approach to enhancing solar cell performance.

This study investigates the enhancement of solar cell performance through temperature reduction using coated V-trough concentrators. Thin film coatings with varying thicknesses (100, 200 and 300 nm) were deposited on the top surfaces of V-troughs via physical vapor deposition (PVD). The analysis focused on the optical (transmittance, reflectance, absorption), thermal, and electrical characteristics, supported by structural and morphological evaluations using XRD and SEM. A comparative approach was adopted, examining three configurations: (1) bare cells, (2) cells with uncoated V-troughs, and (3) cells with coated V-troughs. The results highlight the impact of coating thickness on light management, heat dissipation, and overall cell efficiency. In addition, annealing was considered for the optimal thickness to further improve performance. This work demonstrates a practical pathway for improving photovoltaic efficiency under high-irradiance conditions, aligning with sustainable energy goals.

1. Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

Proton Irradiation and In-Situ Time-of-Flight Elastic Recoil Detection Characterisation of Perovskites for Space Photovoltaics

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Space photovoltaics must achieve both high specific power and resilience to spacefaring conditions, predominantly incident proton radiation. Wide band gap perovskite solar cells fill this niche as a cheaper alternative, with recent studies highlighting their radiation tolerance, especially to proton bombardment [1,2]. However, perovskite cells are still prone to degradation, particularly pertaining to the lighter elements associated with organic cations, leading to an overall reduction in power conversion efficiency [3].

To investigate the distribution of light elements across the near surface of perovskites, the ion beam technique Time-of-Flight Elastic Recoil Detection (ToF-ERD) was used to analyse $Cs_{0.17}FA_{0.83}Pb(I_{0.6}Br_{0.4})_3$ films [4]. These perovskites were subjected to an array of conditions including implantation with 80 keV protons for a fluence of 2×10^{14} ions/cm^2 to simulate low Earth orbit environments. Alongside this, samples were exposed to illumination and biasing *in-situ* throughout ToF-ERD measurements to mimic operating conditions.

ToF-ERD was carried out using 14.6 MeV $^{127}I^{8+}$, whereby heavy incident ions elastically forward recoil atoms from the sample at a near glancing angle. The velocity and energy of the recoils are then measured with two timing foils and a gas ionisation chamber. An example ToF-ERD histogram is shown in Figure 1, illustrating the separation of lighter elements and the correlation of element concentrations with depth, due to inelastic collisions with electrons within the material. This simultaneous measurement yields an enhanced mass resolution, enabling determination of high-resolution unambiguous depth profiles of H, C, N and Br. A reduction in the surface Br was observed under illumination, consistent with the light-induced volatilisation of $PbBr_2$, demonstrating the potential of the technique in tracking ion migration in films to further understand perovskite degradation mechanisms.

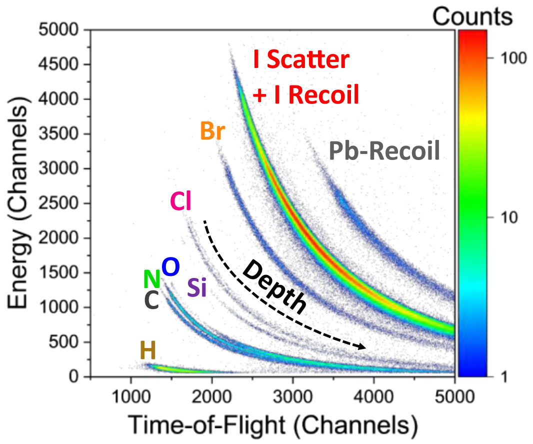

Figure 1 ToF-ERD histogram of a measured perovskite, illustrating the separation of light elements through the film.

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A zinc grid - conducting polymer transparent electrode for organic photovoltaics

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Whilst zinc (Zn) is the fifth most electrically conductive metal, thermally evaporated Zn has been sparsely used as an electrode material for organic photovoltaics (OPVs) - likely due to the difficulty in achieving uniform film growth on many technologically relevant substrates, including glass and polyethylene terephthalate, and the propensity of Zn to contaminate vacuum systems due its low sublimation temperature high vapor pressure.

The Hatton group have recently reported a Zn grid electrode with micron-sized line width and 10 µm line spacing (pitch), fabricated using the unconventional approach of condensation coefficient modulation, and have demonstrated application as the transparent electrode in OPVs [1]. However, in that proof-of-concept work the grid pitch was constrained to 10 µm by the low conductivity of the aluminium doped zinc oxide layer spanning the gaps between grid lines, which limited the amount of light that could be coupled into the OPV device.

This talk will present new work focused on developing a way to combine a Zn grid fabricated by condensation coefficient modulation with the conducting polymer poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) so that the grid pitch can be increased by an order of magnitude. This modification opens the door to achieving OPV power conversion efficiency comparable to that achieved using a conventional indium-tin oxide coated glass electrode. The performance of OPV devices using this novel transparent electrode will be compared with that using a conventional indium-tin oxide transparent electrode, including device stability. Additionally, new insights into the critically important role played by the organometallic Zn nucleation layer, copper acetylacetonate, will also be presented.

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The Effect of Coastal and High-Soiling Environments on Porous Silica Anti-Reflection Coatings vs Anti-Soiling Coatings

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Photovoltaic (PV) modules cover glass features an anti-reflection coating (ARC) made from a thin layer of porous-silica (SiO_2) on the surface, that reduces reflections due to its lower refractive index [1]. Porous SiO_2 ARC are effective at reducing reflection losses but compromises the durability of the coating. Additionally, these coatings are superhydrophilic which increase the likelihood of soiling and salt deposits to adhere to the surface of the cover glass. In salty conditions such as coastal and nearshore PV, and in environments with high soiling rates such as in the MENA / SEA Region, and in agriculture PV, it is unknown how much benefit is gained by using porous SiO_2 ARC, and whether anti-soiling coatings (ASC) would provide greater power output efficiency over the lifetime of the PV module [2]. With incentives towards increased deployment of PV in coastal conditions, as well as in areas where sun activity is greatest, understanding how these coatings operate in extreme environmental conditions can determine their industrial feasibility and technological development.

This study investigates the performance and durability of commonly used porous SiO_2 ARC against a multi-layer AR with a thin polymer ASC applied on top. The coatings were exposed to salty spray mist, to simulate coastal and floating conditions, and a dew-dust-dry (DDD) soiling chamber, to simulate high soiling environments found in the deserts of North America.

SEM images and UV/Vis spectroscopy revealed that salt spray mist causes the porous SiO_2 ARC to mechanically fail due to coating abrasion and embedded salt crystals, Figure 1a, that reduced the optical transmission by an absolute ~3 T% over 5 cycles, compared to the combined AR & ASC which degraded by as little as ~1.4 T% and retained its hydrophobic properties. In the high soiling environment, the porous SiO_2 ARC failed to allow light to transmit through the coating due to the cemented dust on the surface caused by the DDD cycles. The porous SiO_2 ARC was also found to have performed worse than the control SLG in this test, figure 1b. With increased susceptibility to salty conditions and soiling, this testing has shown that porous SiO_2 ARC is unfit for extreme environmental conditions, with increased economic losses that would also be caused due to an increase in cleaning frequency. For future PV deployment in these environments, a multi-layer ARC with hydrophobic top layer is the preferred choice to mitigate environmental losses and reduce maintenance costs.

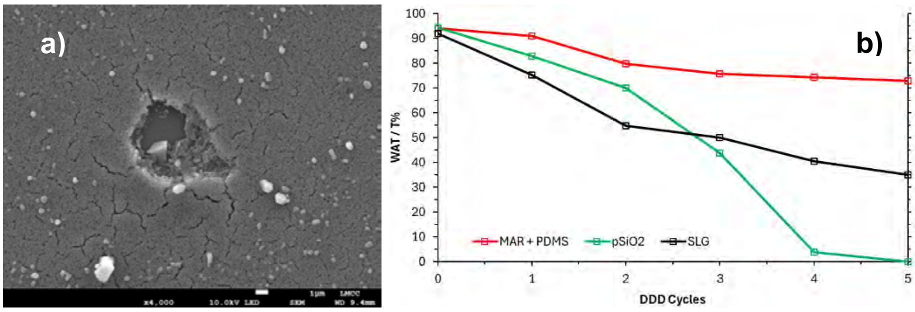

Figure 1a) SEM micrograph of porous silica after 5 cycles of salt-spray. b) degradation of porous silica against MAR & AS coating after 5 cycles of DDD testing.

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1.Perovskite, organic, tandems and DSSC photovoltaics

First-Principles Investigation of Band Alignment and Defect-Induced Electronic States at 2D–3D Perovskite Interface

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Abstract:

2D/3D hybrid perovskite architectures have attracted increasing interest due to their potential to combine high environmental stability with excellent optoelectronic performance. However, several critical band-structure issues—such as band misalignment, quantum-well-induced band bending, deep-level defect formation, and weakened electronic coupling—remain insufficiently understood at the interface and limit further efficiency improvement. In this work, we employ density functional theory (DFT) to investigate the electronic structure of the $(CH_3(CH_2)_3NH_3)PbBr_4$ (PEA-$PbBr_4$) / $CsPbBr_3$ perovskite interface. Particular attention is given to Br vacancies, which introduce deep trap states and are known to directly suppress open-circuit voltage in bromide perovskite devices

Our results show that the wide bandgap and strong quantum-confinement characteristics of PEA-$PbBr_4$ cause pronounced conduction- and valence-band offsets relative to $CsPbBr_3$, creating potential barriers for charge extraction. The insulating nature and low dielectric constant of the PEA organic spacer weaken wave-function overlap across the interface, leading to localized band flattening and reduced carrier mobility. Defect calculations further reveal that Br vacancies at the interface introduce deep trap states with energies on the order of a few hundred meV, promoting non-radiative recombination and contributing to open-circuit-voltage losses.promote non-radiative recombination and contribute to open-circuit-voltage losses. We also explore how variations in interfacial atomic arrangement and organic-chain orientation could be leveraged to mitigate band discontinuities, suppress defect states, and establish more favorable charge-transfer pathways.

6. Photovoltaic systems solar irradiance and monitoring, policy, sustainability, market development and life cycle analysis

Grid-tied photovoltaics with energy storage; assessing the impact of weather data sources and software selection on the accuracy of performance modelling

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Grid connected photovoltaics (PV), both residential and commercial as well as utility scale installations are now often coupled with battery storage. Following this trend software tools allow for the simulation of battery storage as an integral component of these systems. These tools include specialized PV simulation software packages such as SAM, PVsyst, PV*SOL, as well as whole building performance simulation tools, such as EnergyPlus. Although the accuracy with which the performance of grid connected photovoltaics can be simulated has been extensively investigated [1], in the cases that energy storage is included, the evaluation of simulation accuracy has attracted less attention. Likewise, little work has been done when whole building performance simulation tools are used instead of specialized software.

It is well known that performance modelling results are influenced primarily by weather input, such as solar irradiance, wind and temperature. Several sources of historic weather data are available. Era5 provides global reanalysis weather data with a broad set of variables. Copernicus Atmosphere Monitoring Service (CAMS) provides widely used solar radiation products and SARAH3 climate data derived from satellite observations are also widely used. Key question is therefore how the discrepancies in data from these weather data sources may influence the accuracy of simulation results in systems with energy storage.

To address this question the present work models a grid connected residential rooftop PV system with battery storage in the North-West of England using PVsyst and then Design Builder and EnergyPlus. It uses a selection of sources for meteorological input and validates the results using on-site monitored data. The power dispatch strategy is prioritizing the charging of the batteries over grid injection [2].

The results reveal how the simulation output discrepancies are driven by discrepancies in meteorological inputs and how the energy balancing functionality of storage may contribute to the enhancement or reduction of the discrepancies in the output. Hence, this research provides valuable insights for professionals and researchers in selecting the most appropriate type of weather data source for the simulations.

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Improving Ambient Slot-die Printed Perovskite Films Using Air Knife Induced Crystallisation.

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Perovskite has emerged as a promising alternative material for use in solar cells, in recent years Perovskite Solar Cell (PSC) devices have achieved a PCE exceeding 26% [1]. However, the most efficient PSCs have a high toxicity, due to the chosen Perovskite materials containing Lead. $Cs_2AgBiBr_6$ (CABB) has emerged as a leading Lead-free Perovskite material for solar cell applications due to its inherent stability and significantly lower environmental footprint compared to lead based alternatives. Despite this, much of the research on CABB devices remains on a small scale. For CABB devices to be produced industrially, scalable techniques must be explored further, to allow for better performing devices. Slot-die coating is a promising technique, with its high material throughput, easily modified parameters and ability to be used in roll-to-roll (R2R) manufacturing, making it an ideal candidate for fast, cheap and scalable production. Fully slot died Lead-Perovskite have been produced, achieving a PCE of 18.13% [2], with this study also producing a fully R2R device with an efficiency of 13.00%. However, producing slot-die CABB films in ambient conditions has its own set of problems, with moisture greatly impacting the crystallisation of CABB films. The air knife is a promising candidate to improve film quality with it allowing for the rapid crystallization of Perovskite crystals, along with its applications in R2R making it an excellent fit with Slot-die printing [3]. This project aimed to improve the crystalisation of CABB crystals in slot-died films to improve device performance. The air knife was used to evaporate the solvent, with the air knife pressure and height being optimised to create more compact and uniform films.

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1.Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

Accurate spectral response and current-voltage measurements of semi-transparent PV devices.

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Semi-transparent photovoltaic (PV) devices allow alternative deployment routes, such as building integrated PV (BiPV) or Agri-PV applications, while they can even be used for 4-terminal tandem configurations. In addition, in most cases semi-transparent PV devices are naturally bifacial.

One of the major challenges of semi-transparent PV devices is their accurate testing. In most cases semi-transparent PV devices are also bifacial, although exceptions exist. When testing them under illumination, light that goes though the PV device can be reflected back towards the PV device from the rear side, either due to any reflectivity of the sample mount, or any background that exists in the testing setup. IEC TS 60904-1-2:2024 states that for testing bifacial PV devices, a non-irradiated background is required, described as having less than 5 W/m^2 incident on the rear side [1]. This is not always possible to achieve, as most temperature control platforms can have significant reflectivity, affecting both spectral responsivity and current-voltage (I-V) testing of semi-transparent PV devices, resulting in significant overestimation of measurement values (mainly current).

We describe a procedure to calculate background irradiance incident on the rear side of a semi-transparent PV device and correct for it to acquire the correct spectral response or I-V curves. We present spectral response and I-V curves on surfaces with different reflectivity and correct to the right measurement values. If the reflectivity of the measurement surface is known, the rear side irradiance can be calculated by measuring the transmission of the sample and the spectrum of the light incident on the front side of the sample. We validate the correction methods using a low-reflectivity surface with 0.8% average reflectivity. Non-corrected spectral response curves show deviations of up to 9% from the low-reflectivity surface value. For I-V testing, average deviations of 7% are observed when not using a low-reflectivity surface.

Such corrections are rarely mentioned in the literature when reporting measurements of semi-transparent PV devices, which indicates the need for a validated correction method. The correction methodology can be applied in both solar and indoor PV applications and should always be applied when testing semi-transparent PV devices, if rear side irradiance is calculated to be higher than 5 W/m^2.

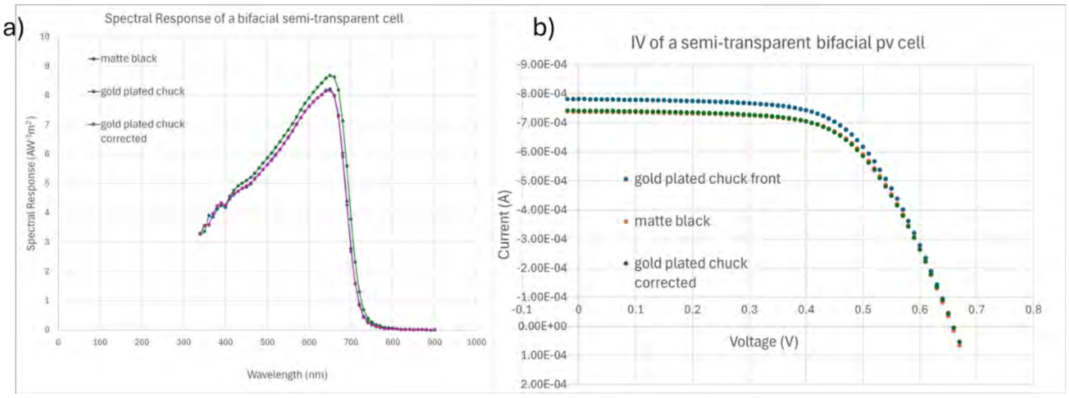

Figure 1. a) Spectral response and corrected spectral response of a bifacial semi-transparent cell on two surfaces, gold plated aluminium and low reflectivity surface. 1b) IV and corrected IV curve of the same bifacial semi-transparent PV cell on the same two surfaces.

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Application of Spin-Coating SnO_2 as Sole Electron Transport Layer in p-i-n Perovskite Solar Cells

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Perovskite solar cells with p-i-n structure (PSCs) have attracted intense interest owing to their rapidly increasing power conversion efficiencies[1]. Achieving high-efficiency PSCs depends on the development of effective electron transport layers (ETLs). Fullerenes and their derivatives, such as $PC_{61}BM$ and C_{60}, have dominated ETL applications in PSCs because of their high electron mobility and compatibility with low-temperature processing[2]. However, the widespread adoption of fullerene-based ETL is hindered by their high material cost and inefficient fabrication processes: thermal evaporation of C_{60} is highly energy intensive, while spin-coating of $PC_{61}BM$ results in 98% of its raw material waste[3]. Inorganic metal oxide ETLs offer a compelling alternative, combining low cost, superior stability, and scalable processing routes[4]. Among them, tin (IV) oxide (SnO_2) has been extensively employed in n-i-p perovskite solar cells, where it exhibits excellent long-term operational stability. Despite these advantages, the use of spin-coated SnO_2 as the sole ETL in PSCs remains largely unexplored, and a systematic understanding of its material processing and interfacial properties is still lacking. Here, we present a comprehensive investigation of spin-coated SnO_2 as an inorganic ETL for PSCs. SnO_2 nanoparticles with controlled sizes were synthesized via hydrothermal routes, dispersed in tailored organic solvent systems to form stable suspensions, and deposited directly onto perovskite layer to form homogeneous, pinhole-free SnO_2 layers. In addition, we explore interfacial materials at the buried SnO_2/perovskite interface to reduce trap density and promote efficient electron extraction. This work will link SnO_2 material synthesis, interface engineering, and defect passivation together, providing a viable pathway toward highly efficient and stable all-inorganic PSCs.

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Adventurous manufacturing of socially-inspired building integrated PV

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As urban environments continue to grow, area suitable for wafer-based silicon photovoltaics (PV) is diminishing and restricted to rooftop-installations. Building integrating PV (BIPV), in the form of roof shingles, louvres, facades and windows, is gaining traction within the market as well as innovative research. This overcomes the challenge of space limitations and provides alternative ways to use PV for clean electricity generation. While much research has focused on improving the aesthetics of BIPV through coloured, transparent, textured or visually blended designs, an under-explored opportunity is patterned PV devices (**Figure 1**) offering unique, individualised opportunities for installation.

A versatile and scalable laser patterning process is developed to create aesthetically enhanced $CuInGaSe_2$ (CIGS) thin-film solar cells (also applicable to CdTe) with solar energy conversion efficiencies comparable to reference, non-patterned devices (~13%). This process can produce a variety of designs with high fidelity and very minor distortions (**Figure 2**), demonstrating its adaptability and appeal to diverse audiences and applications.

A social study supports preference for the appearance of these novel devices (62%) over traditional designs (21%), and finds their presence can positively influence people's perceptions about organisations (69%) or property purchasing decisions (53%). Although positive attitudes were shown for patterned PV concepts, concerns arose about electricity generation losses (by removing active cell area), cost and sustainability. This trade-off received mixed responses with 54% willing to accept electricity reductions for higher aesthetics. Additional costs are expected to be low, due to the fast, scalable nature of the process.

The environmental impact of manufacturing $1 m^2$ patterned module was compared to a non-patterned module using life cycle assessment. All 16 investigated environmental impact categories increase, from additional resource and electricity usage, however these were relatively small (<5%) for most categories (10). Climate change impact was larger (+6.3%), though hotspot analysis shows the patterning process is not a major contributor.

Together, these results show manufacturing, societal and environmental promise for this technology. Future work should address essential factors challenging the real-world application of this product such as scaling-up and compatibility with structural engineering standards.

Figure 1: Patterned PV design concept – also used in the social study survey

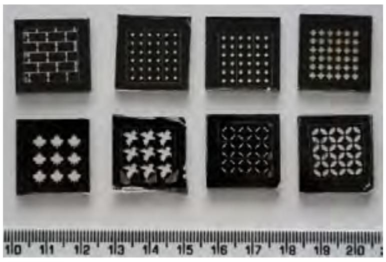

Figure 2: Achieved patterned devices fabricated onto CIGS PV technology

1. Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

Solution-Processed Barium Sulfide Thin Films via Spin Coating and Low-Temperature Sulfurisation

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Barium sulfide (BaS) thin films are of interest as precursor layers for chalcogenide perovskite photovoltaic materials, [1] yet their synthesis has remained largely dependent on high-vacuum vapour deposition techniques. [2,3,4] This work presents a solution-processed route to crystalline BaS thin films via spin coating of aqueous $Ba(OH)_2 \cdot 8H_2O$ followed by thermal sulfurisation.

Characterisation of the as-deposited films reveals rapid conversion of the hydroxide precursor to $BaCO_3$ prior to sulfurisation, making this approach distinct to our earlier sulfurisation method for BaS powder. [5] Figure 1 shows a sharp conversion threshold between 450 °C and 500 °C, with a high sulfur vapour excess required to approach complete conversion. At optimal conditions, films achieve 75–85% phase purity as determined by XRD with Rietveld refinement, with thicknesses of approximately 600 nm on glass substrates.

By combining solution processability with low thermal budgets, this method provides a scalable and accessible route to BaS thin films, facilitating wider investigation of BaS-based semiconductor systems.

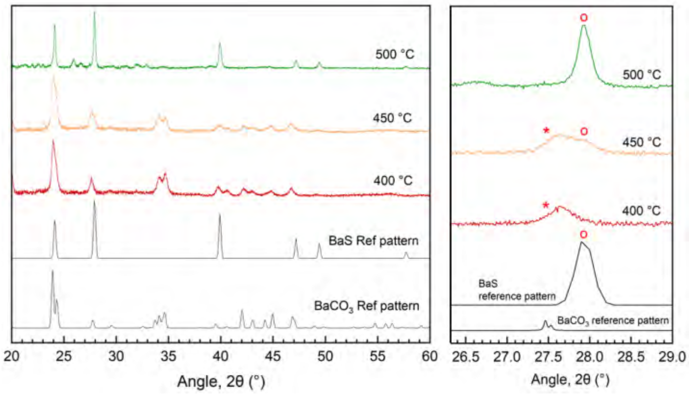

Figure 1 – Diffractograms for temperature variation of annealing

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Initial Testing of Silicon Heterojunction Solar Cells Under Space Environment Stressors

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With the number of satellites being launched each year and their future power requirements both projected to increase over the coming years, alternative space photovoltaic technologies are being evaluated, including silicon heterojunction (HJT) solar cells. The space industry standard GaInP/GaAs/Ge triple junction (TJ) solar cells used today have AM0 efficiencies of around 30%, compared to a roughly 25.1% AM0 record efficiency in HJTs [1]. However, TJ cells have long lead times and are thousands of times more expensive per watt than silicon cells. Therefore, given their high manufacturing throughput, low cost per watt and past heritage of being used in space, modern silicon solar cells are being reexamined for space applications.

Compared to other space photovoltaic materials, the characterization and understanding of modern silicon devices under space environmental stressors is far more limited. Hence, we present some initial results of high-performing silicon HJT solar cells under space environmental conditions, including 160 keV proton radiation and thermal cycling/shock tests.

P-type and N-type HJT devices were irradiated with 160 keV protons, which targeted the front layers of each device as seen in Figure 1a, with a fluence of 2×10^{13} cm^{-2}, equivalent to over 40 years of proton energy deposition in a 500 km polar orbit. Post test characterization showed that front junction P-type devices demonstrated greater radiation resistance compared to rear junction N-type cells (79% compared to 92% efficiency degradation). Although P-type wafers are more radiation resistant [2], as the bulk was not targeted, the junction location, where front-junction devices are more radiation resistant [3], is expected to be the dominant factor dictating radiation resistance in this case. Future tests aim to use higher energy protons and rear irradiation to verify that front junction P-type structures are the most resistant HJT to radiation.

Evaluating thermal performance, P-type and N-type HJT devices were measured across three separate tests: single measurements over a temperature range of 80°C to -120°C under AM0 conditions demonstrated similar behavior between wafer types with N-type samples slightly outperforming the P-type wafers; 100 thermal cycles across a range of 85°C to -40°C with a ramp rate of 1.67°C/min, as seen in Figure 1b, to replicate terrestrial standard IEC conditions, which showed no meaningful degradation, and 100 thermal shocks across a range of 100°C to -80°C with a ramp rate of 16°C/min, as seen in Figure 1c, to replicate the space environment, which were shown to cause a modest efficiency decrease of around 5%, mainly caused by a decrease in fill factor. Harsher ramp rates are currently being tested to evaluate their relationship with HJT degradation, alongside further characterization of the shocked cells.

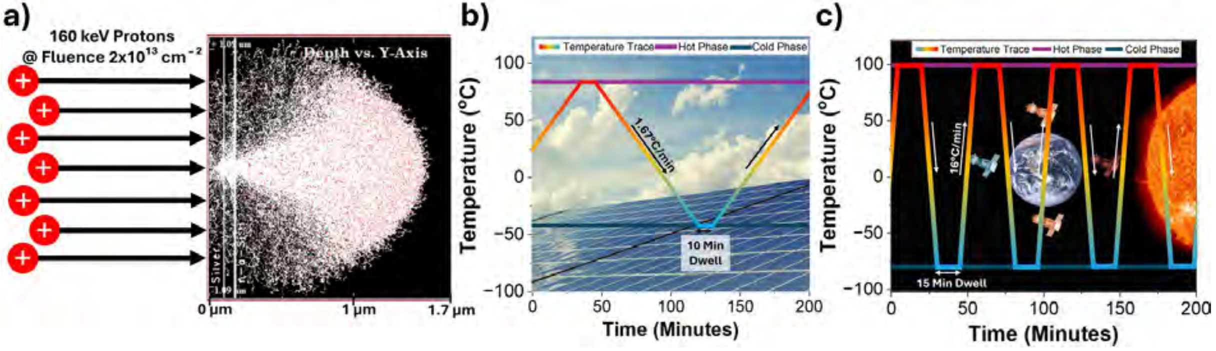

Figure 1: a) 160 keV Proton Simulated (SRIM) Radiation Damage into a Silicon Heterojunction Solar Cell (Zoomed in), **b)** Example Terrestrial and **c)** Space Thermal Shock Test Temperature Traces

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1. Conference Topic

Development of a hybrid transparent electrode for organic photovoltaics based on a fine copper grid and poly(3,4-ethylenedioxythiophene): polystyrene sulfonate conducting polymer

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The transparent electrode is an essential component for organic photovoltaics (OPV) devices and is a key determinant of the cost and range of applications. The transparent electrode must be compatible with low-cost, flexible plastic substrates (e.g. polyethylene terephthalate (PET)) and be fabricated using low-cost materials and fabrication processes. This poster presents recent developments of a novel, high performance, flexible transparent electrode designed for use in OPVs that is based on a fine copper grid and a poly(3,4-ethylenedopxuthiophene): polystyrene sulfonate (PEDOT: PSS) conducting polymer layer. It is shown that the key to realizing this electrode is chemical engineering of the interface between copper grid and PEDOT: PSS layer to minimize contact resistance and maximize stability. The performance and stability of model OPVs using this electrode is presented and compared to devices using indium tin oxide (ITO) coated on PET.

Interface and Bulk Effects of Solution-Based Copper Treatments in CdSeTe/CdTe Solar Cells

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Thin-film cadmium telluride (CdTe) modules lead the global thin-film PV market, with over 30 GW_p of installed capacity [1] and a record laboratory cell power conversion efficiency (PCE) of 23.1% [2]. Despite CdTe's proven track record, p-type doping and back-contact limitations remain obstacles to approaching the Shockley-Queisser PCE limit of 33% [3]. In this study, we systematically investigated the impact of different solution-based copper chloride ($CuCl_2$) treatments on CdSeTe/CdTe devices. The $CuCl_2$ concentration (0-0.4 mM), $CuCl_2$ dipping time (0.5-10 mins), back-surface HCl etching, and post-absorber deposition annealing, were varied to decouple bulk doping effects from back-contact and interface band-alignment effects. Cu-doping led to consistent improvements in fill factor (FF) and reduced series resistance (R_s), accompanied by suppression of current density–voltage (JV) rollover (as observed in Fig. 1a) and enhanced electroluminescence (EL) homogeneity. In contrast, the short-circuit current density (J_{SC}) remained largely unchanged, and the open-circuit voltage (V_{OC}) decreased by ~25 mV. Capacitance–voltage (CV) and drive-level capacitance profiling (DLCP) measurements revealed no significant change in net carrier concentration (as observed in Fig. 1b) across all $CuCl_2$ concentrations, $CuCl_2$ dipping times, or surface treatments, indicating that the observed performance gains are not driven by bulk doping effects. Back-surface HCl etching degraded device performance by reintroducing rollover behaviour and increasing R_s, while annealing alone improved contact quality but reduced V_{OC}.

Optimal performance was achieved using a 1 min dip in 0.2 mM $CuCl_2$ in deionised water, resulting in a peak PCE of 16.2%, with FF of 69.2%, J_{SC} of 30.9 mA/cm^2, and V_{OC} of 758 mV. Ongoing temperature-dependent JV measurements and scanning transmission electron microscopy cathodoluminescence (STEM-CL) analysis aim to directly quantify back-contact barrier heights and spatial recombination pathways associated with Cu incorporation.

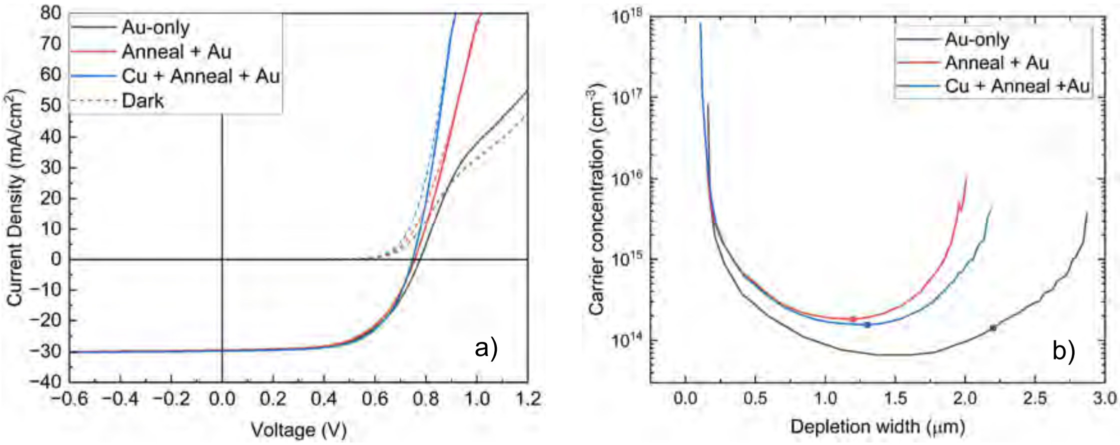

Figure 1: Devices with Au-only, Anneal + Au, and Cu + Anneal + Au back contacts: a) Light and Dark JV curves. b) DLCP-derived carrier concentration vs depletion width.

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[3] I. Chatratin *et al.*, Journal of Physical Chemistry Letters 14, 273 (2023).

PVSAT2026 Poster Presentations

Poster No.	Session - Name	First Name	Last Name	Organisation	Paper Title
1	**Poster Session B (Thursday)**	Fahad	Alharbi	University of Exeter	Enhancing Photovoltaic Efficiency through Coated V-trough Concentrators: Optical, Thermal, and Electrical Investigations
2	**Poster Session A (Wednesday)**	Toluwalase	Agoro	University of Cambridge	Characterising hot carrier effects in ultra-thin III-V solar cells
3	**Poster Session B (Thursday)**	Khalid	Almalki	University of Exeter	Enhancing Thermal Management in High Concentration Photovoltaic (HCPV) Systems Using Copper Oxide (CuO) and Graphene Oxide (GO) Nanofluids: Experimental Investigation and Performance Optimization
4	**Poster Session A (Wednesday)**	Shuhrah	Allami		A zinc grid - conducting polymer transparent electrode for organic photovoltaics
5	**Poster Session B (Thursday)**	Alanoud	Aloufi	Newcastle University	Designing Interfaces and Understanding Ion Transport in Hybrid Perovskites for Optoelectronic Applications
6	**Poster Session A (Wednesday)**	Michele	Danesi	National Physical Laboratory	Standardised Characterisation and Comparison of Indoor Photovoltaic Devices
7	**Poster Session B (Thursday)**	Jie	Chen		Development of Ecofriendly Organic Solar Cells with High Stability
8	**Poster Session A (Wednesday)**	Zeyad	Elsayed	Loughborough University	Interface and Bulk Effects of Solution-Based Copper Treatments in CdSeTe/CdTe Solar Cells
9	**Poster Session B (Thursday)**	Sicheng	Deng		Application of Spin-Coating SnO2 as Sole Electron Transport Layer in p-i-n Perovskite Solar Cells
10	**Poster Session A (Wednesday)**	Jake	Forsyth-Hughes	Northumbria University	The effect of the sulphurisation rate on Bi2S3 films prepared by thermal vapour sulphurisation of bismuth precursors
11	**Poster Session B (Thursday)**	Oliver	Dodd	University of Liverpool	Improving Ambient Slot-die Printed Perovskite Films Using Air Knife Induced Crystallisation
12	**Poster Session A (Wednesday)**	Aikaterini (Katerina)	Fragaki	University of Lancashire	Grid-tied photovoltaics with energy storage; assessing the impact of weather data sources and software selection on the accuracy of performance modelling
13	**Poster Session B (Thursday)**	Yuxiang	Guo	University of Warwick	Development of novel small-molecule electron transport materials for tin perovskite photovoltaics
14	**Poster Session A (Wednesday)**	Amna	Ijaz	Northumbria University	Reaction-Time Engineering of TiO_2 Nanostructures for Electron Transport Layers

15	**Poster Session B (Thursday)**	shaojun	Hao	Newcastle University	First-Principles Investigation of Band Alignment and Defect-Induced Electronic States at 2D–3D Perovskite Interface
16	**Poster Session A (Wednesday)**	Imalka	Jayawardena	University of Surrey	Perovskite Photovoltaics in Space: Resilience Under Ion Irradiation
17	**Poster Session B (Thursday)**	David	Keeble	University of Dundee	Investigation of vacancy point defects in CdSexTe1-x semiconductors
18	**Poster Session A (Wednesday)**	Luke	Jones	Loughborough University	The Effect of Coastal and High-Soiling Environments on Porous Silica Anti-Reflection Coatings vs Anti-Soiling Coatings
19	**Poster Session B (Thursday)**	Lavanya	Malarkannan	National Physical Laboratory	Accurate spectral response and current-voltage measurements of semi-transparent PV devices
20	**Poster Session A (Wednesday)**	Amruta P	Joshi	Warwick Manufacturing Group, University of Warwick	Assessment of laser material interactions for improving end-of-life management of silicon solar photovoltaic modules using COMSOL modelling
21	**Poster Session B (Thursday)**	Callum	McAleese	Surrey Ion Beam Centre	Proton Irradiation and In-Situ Time-of-Flight Elastic Recoil Detection Characterisation of Perovskites for Space Photovoltaics
22	**Poster Session A (Wednesday)**	Austin	Kay	Swansea University	Thermo-Opto-Electronic Analyses of Space-Based Photovoltaics
23	**Poster Session B (Thursday)**	Yongtao	Qu	Northumbria University	Sb2Se3 Photoreceiver Enabling Energy Harvesting and Optical Signal Transmission
24	**Poster Session A (Wednesday)**	Anil	Kumar	University of Warwick	Silicon Surface Passivation by ZnO/Al2O3 Stack with Controlled Interlayers
25	**Poster Session B (Thursday)**	Aryaveer	Singh	University of Dundee	Identification of vacancy-related point defects in inorganic perovskite halide semiconductors
26	**Poster Session A (Wednesday)**				
27	**Poster Session B (Thursday)**	Will	Tetlow	Northumbria University	A Low-Temperature, Low-Emission Solid-State Route to Barium Sulfide
28	**Poster Session A (Wednesday)**	Kieran	Landregan	University of Edinburgh	The Development of Novel, Dopant-Free Hole Transport Materials for Perovskite Solar Cells
29	**Poster Session B (Thursday)**	Connor	Tynan	National Physical Laboratory	Improving PV system degradation forecasting using machine learning ensembles and a combination of real and synthetic system data
30	**Poster Session A (Wednesday)**	Dolapo	Onabule		Bulk and Microscopic Characterisation of Solar Cell Materials with Multimodal Spectroscopy
31	**Poster Session B (Thursday)**	Bethany L	Willis	Northumbria University	Adventurous manufacturing of socially-inspired building integrated PV

32	**Poster Session A (Wednesday)**	Tommy	Richards	University of Surrey/SSTL	Initial Testing of Silicon Heterojunction Solar Cells Under Space Environment Stressors
33	**Poster Session B (Thursday)**	Elin	Worsley	Swansea University	Fabrication of Laser Interconnected Solar Perovskite Modules
34	**Poster Session A (Wednesday)**	Fátima	Santos	University of Porto	Solvent dependent charge transfer dynamics in efficient and stable indoor copper-mediated DSSCs
35	**Poster Session B (Thursday)**	Weicheng	Xu	University of Warwick	Development of a hybrid transparent electrode for organic photovoltaics based on a fine copper grid and poly(3,4-ethylenedioxythiophene): polystyrene sulfonate conducting polymer
36	**Poster Session A (Wednesday)**	Will	Tetlow	Northumbria University	Solution-Processed Barium Sulfide Thin Films via Spin Coating and Low-Temperature Sulfurisation
37	**Poster Session B (Thursday)**	Maoqing	Zhi	University of Edinburgh	Eco-friendly high open-circuit voltage organic solar cells enabled by PDI-derived acceptors

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